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PHYSICS DIVISION

PROGRESS REPORT
for Period Ending September 30, 1996

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INTRODUCTION

This report covers the research and development activities of the Physics Division for the 1995 and 1996 fiscal years, beginning October 1, 1994, and ending September 30, 1996. The activities of the Division continue to be concentrated in the areas of experimental nuclear physics, experimental atomic physics, and theoretical nuclear and atomic physics. In addition, there are smaller programs in plasma diagnostics and data compilation and evaluation. During the period of this report, there has been considerable success in bringing the Holifield Radioactive Ion Beam Facility (HRIBF) into routine operation. The budgets of the nuclear physics portion of the Division have increased each year in nearly all areas, and several new members have been added to the Division research and development staff.

On August 30, 1996, the HRIBF successfully accelerated its first radioactive ion beams, ^{69}As and ^{70}As. Prior to this, the heart of the facility, the RIB injector system, was completed, including installation of a remote handling system for the target/ion source assembly. Target and ion source development is likely to be the technical key to success of the HRIBF. We have expanded our efforts in those development areas. Of special note is the development of highly permeable composite targets which have now been shown to allow release of difficult-to-produce radioactive ions such as ^{17,18}F. A summary of the HRIBF work is provided in Chapter 1, along with supporting activities of the Joint Institute for Heavy Ion Research.

The nuclear structure and astrophysics experimental program covers a broad spectrum of activities centered largely on the use of heavy ions. Particularly emphasized are programs in nuclear structure, spectroscopy of giant resonances, and nuclear astrophysics. During the reporting period members of this research program devoted much of their time to development, installation, and commissioning of new experimental apparatus for the HRIBF. Results from this past year's work are presented in Chapter 2.

The relativistic heavy-ion experimental program continues at CERN and at the Brookhaven AGS. This reporting period covered the peak of activities for the CERN WA98 experiment. The final run on that experiment was held in late 1996. Work on the PHENIX project constitutes a major responsibility of the Division, and this reporting period has seen a significant increase in PHENIX-related work. These activities are discussed in Chapter 3.

A continuing major area of experimental research for the Division is atomic physics. This activity is concentrated in two groups: accelerator-based atomic physics, centered primarily at the EN Tandem, but extending to ultrarelativistic energies at the CERN SPS; and atomic physics in support of fusion energy, based primarily at the ECR ion source facility. These programs also operate, respectively, the EN Tandem and the ECR Ion Source Facility as "user resources." A report on these activities is given in Chapter 4.

The theoretical physics activity in the Division concentrates on the areas of atomic physics, nuclear physics, nuclear astrophysics, and physics at the nuclear-particle interface, with a particular emphasis on applications of high-performance computing. These efforts, which represent independent studies as well as support to the experimental program, are presented in Chapter 5. Included in this chapter are results of work associated with the Center for Computationally Intensive Physics and work involving long-term theory visitors of the Joint Institute for Heavy Ion Research.

The Division has two programs in data compilation and evaluation. The work of the Atomic Physics Data Center and our effort as part of the National Nuclear Data Center are summarized in Chapter 6.

The report concludes with general information on publications, Division activities, and personnel changes.

F. E. Bertrand
January 1997

1. HOLIFIELD RADIOACTIVE ION BEAM FACILITY

OVERVIEW

On June 30, 1992, the HHIRF ceased operation as a national user facility, and, soon afterward became a project to develop an isotope separator on-line (ISOL) based radioactive beam facility, the HRIBF. On August 30, 1996, the HRIBF successfully accelerated its first radioactive ion beam (RIB). In January 1997, we hope to carry out our first PAC approved experiments, and begin routine operation as a national user facility supporting the U.S. and international nuclear science community. This report covers the last half of the challenging, intense, and exciting four years during which this transformation from HHIRF to HRIBF was accomplished.

Like any user facility in nuclear physics, HRIBF is concerned both with beam production, and with the development and support of experimental equipment. Our beam production hardware is comprised of three complex systems, the ORIC, the 25-MV tandem accelerator, and the RIB injector system. The two accelerators, ORIC and the tandem, were inherited from the HHIRF, the RIB injector system was conceived, designed, commissioned, and constructed from scratch.

The RIB injector system (RIBIS) is the heart of HRIBF. It consists of the 300-kV injector HV platform, the target/ion source, a charge exchange cell, the first and second stage mass separators, and a variety of ion-optical equipment. A robotic radioactivity handling system, while not strictly a part of the beam production system, is a crucial ancillary system of the RIBIS. The second stage mass separator, the last major component of the RIBIS, was installed in the summer of 1995. In October 1995, a stable beam generated in the ion source on the HV platform was transported through the entire RIBIS, and accelerated by the tandem. This first commissioning run showed that while all components were operable, a great deal of work remained to be done to achieve the transmission and general ion optical performance required for HRIBF. After an intense period of work, interrupted by shielding reconfiguration and installation of the remote handling system, we were able to demonstrate, in a new series of stable beam commissioning runs in the summer and fall of 1996, that the entire RIBIS was performing at or beyond specifications. Stable beams were transported from the ion source to the tandem with essentially no losses in any element of the system other than the charge exchange cell. As a part of this work some very nice measurements of energy-loss straggling of 50 keV Ge beams in thin Cs vapor were carried out. Knowledge of this straggling is crucial to successful use of the second stage mass separator for isobar separation.

The main components of the remote radioactivity handling system (RHS) including a robotic arm manufactured by PaR Systems, Inc., were installed in the spring of 1996. The RHS is now completely operative, able to remove and reinstall target/ion source assemblies remotely, and to transport them in a sealed container to room C110 for storage.

ORIC was originally built as a high current light ion accelerator. In the early 1970s it became a heavy-ion machine, and finally, at the end of the 1970s, was modified to serve as a booster for the 25-MV tandem accelerator. For HRIBF, ORIC has come full circle; it is again a high current hydrogen and helium beam accelerator – but it is now more than three decades old – and for the last 15 years, it has been only a part-time machine. The job of making ORIC run reliably and efficiently is a very large one and will continue to absorb much effort from the HRIBF staff. We are now in the second year of a four-year, \$1.8M

AIP project dedicated to the improvement of ORIC. Major progress has been made, but much remains to be done. Reliability, high-current operation, and routine operation at the top of the proton energy range (65 MeV) are all key issues. Improvement of ORIC is our highest accelerator system priority.

The tandem, in contract to ORIC, is an extremely reliable machine and an inexpensive machine to operate. The biggest challenge with the tandem will probably be learning to operate it effectively with the very small injected beam intensities provided by the RIBIS. Consequently, we have devoted considerable effort to development of low intensity beam diagnostics, both inside the tandem pressure vessel, and in beam lines.

The control systems used to operate ORIC and the tandem were inherited from HHIRF along with the accelerators. These systems date from the beginning of HHIRF and are based on 1970s vintage hardware. The systems for the two accelerators have different architectures and are based on different, but equally obsolete, computers and hardware. They have become almost unmaintainable. We are moving aggressively toward a unified, modern system for all the HRIBF accelerator systems and beam line hardware, based on the V-system tool kit from Vista Controls. This system will be more reliable, and much easier to reconfigure and maintain than the systems it replaces. The Vista system is fully implemented and routinely used to control the RIBIS; the functions of the ORIC and tandem control systems are being moved to the new system as quickly as possible. We expect to be completely free of reliance on the old systems by late summer of 1997. Our efforts in this area will then be turned to optimizing the architecture and performance of the unified Vista based system.

These accelerator systems developments are essential, but the keys to the success of HRIBF are beam development and associated target and ion source issues. The resources available to us are increasingly being concentrated in these areas. At this time, we have three development teams working in close collaboration on different aspects of these problems. A target and ion source research team works on the design of high-power targets and the development and initial testing of new ion source concepts. An in-beam testing and evaluation team uses low power proton and deuteron beams from the 25-MV Tandem to do target and ion source tests and activation release studies, and heavy-ion beams for implantation release studies. The third team is responsible for commissioning and operation of the RIB injector and the development of beams for research.

The in-beam development team played a crucial role in the development of our initial As demonstration beams. They have also achieved breakthroughs in demonstrating the release of ^{17,18}F from a unique thin-fiber mesh Al_2O_3 target and succeeded in producing beams of the flourine isotopes.

Ion source development has moved at a truly remarkable pace. It is impossible to do justice to the scope of these developments in a small space – only a few highlights will be mentioned. Of crucial importance was the design and fabrication of a simple, easily assembled and mechanically robust electron beam plasma (EBP) ion source, which should become our standard workhorse for HRIBF beam production. It is now being tested and refined. Development of negative ion sources which might be used for radioactive fluorine beams has been given a high priority. A number of promising ideas have been investigated and encouraging results demonstrated on the ion source test platform, including a direct extraction negative ion EBP source, and novel implementations of negative surface ionization techniques. Important developments have also been made in molecular dissociators designed to be implemented in a variety of our sources. Quick and efficient off-line characterization of various performance characteristics of ion sources is crucial to efficient development and operation of HRIBF; our ion-source R&D group has made truly innovative developments in this area.

Target development is very likely to be the technical key to the success of HRIBF. HRIBF target/ion source R&D staff have developed the general concept of a highly permeable composite target based on an open carbon fiber matrix; the target material would form a very thin outer layer on this matrix. This concept has been demonstrated to be very promising; implementation of the concept for production of a variety of physically interesting beams will provide us with many challenges.

Our near-term plans are to provide ^{69,70,71}As beams (and possibly Ga and Se from the same target) for initial experiments and to complete development of ^{17,18}F beams for astrophysics research as quickly as possible. Our longer term beam development plan is driven by the wishes of our user community, tempered by the physical and chemical realities of production, release and ionization, and the time scales imposed by decay half lives. At present, ^{58}Cu and ^{63}Ga are our top priorities for nuclear structure, while, after flourine, isotopes of sulfur and silicon will be pursued for astrophysics. Within a year of beginning operation, we hope to begin to produce neutron rich beams from proton induced fission of actinide targets. For the most part, beam development issues are much better understood for this system than for those used to produce proton rich beams. However, use of actinide targets will present more severe regulatory and radiation handling problems.

It must be realized that development of each beam is a research project in itself, involving diverse aspects of metallurgy, surface physics, high-temperature chemistry, etc. We are moving aggressively to enhance our capabilities to do target/ion source and beam development research, including collaboration with groups external to ORNL as well as members of the Chemical and Analytical Sciences Division and the Metals and Ceramics Division at ORNL.

Once we have RIBs, we must be ready to do experiments with them. These experiments will face many technical challenges unique to RIB physics. We have made great strides over the last two years on the two large experimental end stations, the RMS and the DRS, upon which the nuclear structure and nuclear astrophysics research programs will be based. The RMS is essentially complete and ready for the first experiments. The DRS should be ready for the first flourine beams.

The User Organization of the Holifield facility remained intact throughout the period of transformation of HHIRF into HRIBF, providing help, encouragement, and advice during this process. The PAC was re-established in October 1994, initially to provide scientific advice to facility and Division management. Letters of intent were solicited in the summer of 1995; thirty-four were received. Proposals were solicited in the summer of 1996 for experiments with radioactive arsenic isotopes or for stable beam experiments related to RIB physics. 960 hours of RIBs were requested and 800 hours approved; 2008 hours of stable beam were requested and 1000 were approved.

ACCELERATOR SYSTEMS, OPERATIONS AND DEVELOPMENT

ORIC OPERATIONS

J. D. Bailey,[1] D. T. Dowling, R. C. Juras, S. N. Lane, S. W. Mosko, D. K. Olsen, J. W. Sinclair, B. A. Tatum

ORIC has operated for over 400 hours during the past two years for beam development purposes. Effort has centered on light-ion production for ORIC's role as a driver for radioactive beam production.

The nominal requirements for ORIC beams which will be utilized in radioactive beam production are shown in Table 1.1 along with development progress during this reporting period. Beam intensities have been intentionally limited during machine studies to minimize activation of accelerator components.

Table 1.1. Beams required for RIBs

Beam	Requirements	Beam Extracted During Development Period
H^+	50 MeV, 20-40 μA	42 MeV at 68% extraction efficiency, 0.20 μA extracted
$^2H^+$	50 MeV, 20-40 μA	49 MeV at 38% extraction efficiency, 0.40 μA extracted
$^4He^{2+}$	75 MeV, 20-40 μA	75 MeV at 33% extraction efficiency, 1.60 μA extracted

The first radioactive beams have been produced with proton beams at an energy of about 40 MeV. Consequently, these beams have the highest priority. Proton energy of 50 MeV is desired, but thus far has been unattainable. The maximum frequency tunable by the rf system is about 20.1 MHz, but the rf power available is not sufficient to reach normal dee voltage of 70 KV unless the frequency is limited to 19.1 MHz. When the cyclotron is tuned for 50-MeV protons, the maximum radius at which beams can be extracted is only 29 inches. Consequently, the actual beam energy is only 42 MeV.

All beams thus far have been produced with the original central-region geometry and magnetic field optimization via painstaking operator tuning. Central-region design optimization is under way using the Michigan State geometry. New central-region geometry voltage holding tests have been successful with the rf system operating at 12.8 MHz and a dee voltage setting of 70 KV on a nominal 0.25" gap between the source chimney and puller electrode. It is expected that proton beam energy of 50 MeV will be achievable with the improved central region.

ORIC light-ion beams were transported to the target/ion source located on the 300-kV RIB injector platform in room C-111S. The first radioactive beam at the HRIBF was produced with a 42-MeV proton beam incident on a liquid germanium target. The ^{70}Ge(p,n) reaction resulted in a ^{70}As beam which was accelerated by the 25-MV tandem accelerator. The beam was produced under the guidelines for low-intensity commissioning which limit proton beam intensities to ~100 nA.

An exchange of Model 4648 power amplifier tubes in the rf system was recently accomplished. The in-service tube developed a cooling problem due to water passage clogging with resin beads that inadvertently broke loose in our deionized water cooling system. The affected tube was on line since about 1975, and has logged over 60,000 hours of operation. It was replaced with a standby tube that had logged about 10,000 hours before 1975 and has recently served a few hundred hours on loan to the NSCL cyclotron at MSU. The clogged tube was cleaned and is ready to run again.

1. ORNL and the Joint Institute for Heavy Ion Research, Oak Ridge, TN.

ORIC DEVELOPMENT

J. D. Bailey,[1] D. T. Dowling, R. C. Juras, S. N. Lane, S. W. Mosko, D. K. Olsen, J. W. Sinclair, B. A. Tatum

ORIC development is presently directed toward upgrading major accelerator components to assure long-term reliability in service as the RIB driver. Minimization of personnel radiation exposure and elimination or relocation of radiation sensitive components are major considerations.

Controls System

An ongoing ORIC controls upgrade is in progress. Eventually, all controls will be implemented on the Vista Control System. The primary hardware interface to magnetic field devices is established through Allen-Bradley programmable-logic controllers, PLCs, with other components such as vacuum gauge controllers being interfaced through VME serial I/O modules. The PLCs are ethernet-compatible and result in a reliable, flexible system with simplified device interlocking and cabling.

The existing Modcomp computer and interface system was mostly replaced by Vista during the past two years and it should be fully decommissioned by mid-FY97. Many components with controls that were heretofore hardwired are now on Vista, including some of the rf system. All power supply readouts that formerly interfaced with digital voltmeter, DVM, via a crossbar scanner, are now monitored via Vista. Cabling was replaced and most wiring termination and control interfacing is now external to room C-109 (the cyclotron vault) which will be subject to high radiation fields when the cyclotron is operated at high-ion-beam intensity.

Internal Beam Diagnostics

The primary internal ion beam diagnostic device in ORIC is a radial probe which is movable from the central region through extraction radius. Various probe configurations were utilized in recent machine studies. A four-fingered device, which is presently in use, provides both radial and axial beam intensity measurements. Software was developed to automate the scanning process with both graphing and archiving capabilities. Measurements of the required light-ion beams have been taken with the original central-region geometry.

A three-segment probe senses radial position of extracted ion beams in the region between the compensated magnetic extraction channel and the output beam port. A new probe was designed with the former center segment divided into four axial segments. Thus the probe will soon be able to provide both radial and axial position information.

Ion Source and Central Region

New central-region components based on concepts developed at Michigan State University were designed and fabricated. Installation will be completed early in FY97. The new central-region geometry will improve ion beam turn separation that should result in higher beam extraction efficiency and minimal machine activation from planned increases in beam intensity.

The new central-region geometry requires a new beam puller assembly that extends outward from the dee. Several design changes were necessary in the ion source assembly to accommodate the puller and much attention was given to source servicing problems. The heads and the arc chimney are fabricated from OFHC copper, while the cathodes, the arc apertures, the extraction aperture, and the cathode mounts are fabricated from tantalum. The ends of the heads were re-shaped to reduce the electric field between the heads and the dee, and the puller. Access panels for cathode servicing were moved from the tips to the sides for faster and easier cathode replacement. Each cathode is now installed or removed with its mounting assembly so that the cathode-arc aperture can be set before the cathode is actually installed in the source head.

The ion source cathode design features a reduced cathode stem cross-section that reduces heat transfer from the cathode to the water-cooled high-voltage rod. The arc apertures on each end of the chimney are now separate plates that simplify fabrication. The gas feed was replaced with a more compact system that utilizes stainless steel components and vacuum grade fittings.

RF System

The highest priority in upgrading the ORIC rf system is the replacement of the anode high-voltage power supply for the Model 4648 tetrode power amplifier. The PA which operates CW over a 6.7-MHz to 20.1-MHz tuning range, requires anode input of up to 30 A at up to 20 kV. The existing anode power supply, built in 1960, uses vacuum tube rectifiers that are extremely rugged and reliable. Nevertheless, the rectifiers are near the end of their service life, we are out of spare tubes, and replacements are not available. A specification package was prepared for several upgrade/replacement options, and a contract for a new power supply will be negotiated early in FY97. The new power supply will be installed near the original so as to minimize external wiring changes, and to minimize any changeover impact on the cyclotron operation schedule.

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1. ORNL and the Joint Institute for Heavy Ion Research, Oak Ridge, TN.

TANDEM ACCELERATOR OPERATION

R. L. Auble, B. D. Bryant, M. R. Dinehart, C. L. Dukes, D. L. Haynes, C. A. Irizarry, Y. S. Kwon,[1] C. M. Jones, R. C. Juras, S. N. Lane, C. T. LeCroy, M. J. Meigs, G. D. Mills, R. C. Morton, S. N. Murray, D. K. Olsen

During this two-year reporting period, no scheduled experiments were run by the tandem accelerator. The tandem accelerator was operated to provide approximately 140 hours of beam-on-target in FY95 and 600 hours in FY96 to support RIB development and for commissioning of the new RMS. Deuterons and proton beams with energies greater than 25 MeV (up to 40 MeV) were accelerated for the first time. The beams were used for target/ion source studies at UNISOR.

The only significant maintenance required during the reporting period was replacement of energy-analyzing-magnet (BM17) coils. As reported in the previous Physics Division Progress Report,[2] the magnet was operating at the beginning of the reporting period with jumpers across faulty coil turns which caused the effective bending power to be reduced from 320 to 160. Installation of new coils has restored the magnet to full strength.

Tandem accelerator reliability continued to be good, with only four unscheduled tank openings required during the two-year period. Two tank openings were necessitated by failed electronics, one by a failed high-voltage connection to a pump, and one by a bad connection in a power supply. There were two scheduled openings for general maintenance; one long scheduled opening, coincident with BM17 coil replacement, provided an opportunity for installation of electronics for RIB low-intensity diagnostics. Operation of the SF_6 transfer and storage system continued without incident and SF_6 losses remained less than 1% per year.

In the next year, routine operation of the RIB user facility will begin. The tandem accelerator will also provide beam for further RMS commissioning, for DRS commissioning, and for RIB target/ion source studies.

Table 1.2. Tandem beams provided for RIB development for FY95 and FY96

Ion Species	Energies (MeV)
^{1}H	7.5 to 40
^{2}H	7.5 to 30
^{16}O	27.3 to 63.3
^{28}Si	130
^{32}S	120
^{35}Cl	50 to 67
^{37}Cl	67
^{40}Ca	160
^{58}Ni	69.3 to 251
^{63}Cu	80 to 131
^{65}Cu	100
^{69}Ga	75 to 109
^{70}As	140
^{70}Ge	140
^{71}Ga	75 to 110
^{74}Ge	140
^{75}As	80 to 110
^{78}Se	80 to 103
^{79}Br	106

1. ORNL Plant and Equipment Division.

2. M. R. Dinehart et al., *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1994, ORNL-6842* (1994), p. 1-8.

TANDEM LIGHT-ION-BEAM OPERATION

R. L. Auble, M. L. Halbert, C. M. Jones, C.-H. Yu

RIB target/ion source studies utilizing tandem accelerator beams at the UNISOR facility provide a unique opportunity to develop better targets and to understand how to optimize target/ion source operation. Early studies involved implantation of tandem accelerator beams into targets and measurement of subsequent release time. It later became evident that a source of protons and deuterons at energies representative of ORIC beam energies, but at much lower intensity, would also be valuable for target/ion source studies. Tandem accelerator proton energies and intensities, however, were administratively limited to 25nA at 25 MeV because of concerns that activation of tandem accelerator components could cause maintenance difficulties.

In December 1995, three samples were irradiated with 1nA of 40-MeV protons from the tandem accelerator to obtain data required to establish new administrative current limits. The objective was to set a 40-MeV beam current limit such that the induced activity is not significantly greater than that produced by 25 MeV, 25nA proton beams. A neutron detector was also placed approximately one meter behind the target to measure prompt radiation levels. Activities given in Tables 1.3, 1.4, and 1.5 are the initial activity, immediately following irradiation, in nCi/µC (corrected for decay) as measured on 1/4/96. Data for short-lived activities are also available from these measurements, but are not included here since the short half-lives make them less of a concern for routine maintenance.

Table 1.3. Target 1: 8 layers of 0.020" Ti plus 2 layers of 0.025" Stainless Steel (to stop beam). Fluence = 1.12 µC. Neutron dose rate at 1m during bombardment >200 mrem/hr.

			Activity (nCi/µC)		
Layer	E_{in}*(MeV)*	E_{out}*(MeV)*	^{46}Sc(84d)	^{47}Sc(3.3d)	^{48}V(16d)
1-5	40	24.9	5.2	33.7	30.6
6-8	24.9	12.0	1.0	8.3	56.9

Table 1.4. Target 2: 6 layers of 0.025" Stainless Steel (type 316 from gamma spectra). Fluence = 1.73 µC. Neutron dose rate at 1m during bombardment = 200 mrem/hr.

			Activity (nCi/µC)			
Layer	E_{in}*(MeV)*	E_{out}*(MeV)*	^{48}V (16d)	^{51}Cr(27.7d)	^{52}Mn(5.6d)	^{56}C0 (77d)
1-3	40	24.5	10.3	57.6	6.1	6.1
4-6	24.5	0	0	11.6	22.1	16.2

Table 1.5. Target 3: 8 layers of 0.010" Tantalum. Fluence = 1.99 µC. Neutron dose rate at 1m during bombardment = 350 mrem/hr.

			Activity (nCi/µC)	
Layer	E_{in}*(MeV)*	E_{out}*(MeV)*	^{179}Ta (1.8d)	^{178}W (22d)
1-4	40	24.0	9.0	1.4
5-8	24	0	0.2	0

Activation of external stainless steel beam-line components is not considered to be as serious an exposure hazard as activation of titanium internal accelerator components due to less restrictive working conditions. Therefore, based on the above measurements, the limit for 40-MeV protons was set at 10nA extracted beam. In addition, since the beam energy at the terminal will be limited to 20 MeV, the injected beam current limit was set at 20 nA.

AUTOMATIC SHORTING ROD SAFETY VALVE

C. M. Jones, D. L. Haynes, M. R. Dinehart

Motivated by both diagnostic and operational considerations, the HRIBF tandem accelerator is equipped with a shorting rod system which allows subsets of the column structure to be electrically "shorted" so that no potential gradient can exist over the length of the shorted subsets. This system is based on a 1-inch-diameter rod assembly which consists of nylon rods and steel rods which may be assembled in various configurations so as to produce the desired shorting effect. An essential feature of the shorting rod system is that the 1-inch-diameter rod assembly must be inserted through a seal mechanism in the accelerator pressure vessel wall. Thus, during operation of the system, there exists the potential for leakage of the SF_6 insulating gas contained within the pressure vessel.

To minimize the possibility of an accident with this system, the accelerator was originally equipped with a simple valve, positioned within the accelerator vessel, which automatically closes upon withdrawal of the rod assembly. Although this valve has never failed, it was decided that it would be appropriate to provide another completely redundant automatic valve which would also close upon withdrawal of the rod assembly. This contribution describes the design and testing of this second valve.

The essential design criteria of the new valve included the following:

1. Automatic operation with no operator intervention.
2. No external power source.
3. Minimal length.
4. Compatibility with existing components.
5. Low cost.
6. Simple verification of correct operation.

As shown in Fig. 1.1, the valve consists of a cylindrically symmetric housing which is mounted between two flanges of the existing system and held by four studs. The inner surface of the housing is conical. The only moving part of the valve is a steel ball which is captured within the housing.

Upon insertion of the rod assembly, the ball is pushed aside. Upon removal of the rod assembly, the ball falls to the bottom of the conical surface where it then has a circular line contact with the conical surface.

Prior to final installation, the valve was assembled and tested with a source of compressed air to simulate the SF_6 insulating gas. Operation of the valve was excellent. Upon removal of the rod assembly, the valve seals immediately, with virtually no loss of pressurized gas.

ORNL-DWG 96-7932

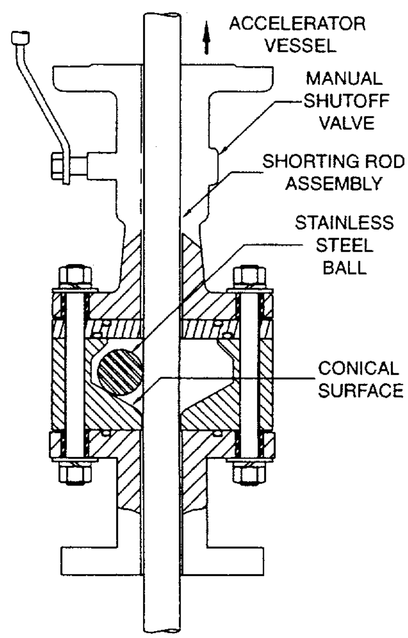

Fig. 1.1. Automatic safety valve.

TANDEM ACCELERATOR ENERGY-ANALYZING MAGNET COIL REPLACEMENT AND CALIBRATION

R. C. Juras, D. L. Haynes, C. M. Jones, M. J. Meigs, D. K. Olsen

Energy-analyzing magnet (BM17) instabilities became apparent during a period of routine accelerator operation in February 1994.[1] The cause of instabilities was traced to an internal short in one of the magnet coils. The magnet was operated for several months with jumpers across the faulty turns which reduced the effective bending power of the magnet from $ME/Q^2 = 320$ to 160. To be able to utilize the magnet at full bending power for the RIB program, new coils of a slightly modified design were purchased and installed in August 1995. In order to remove the old coils (750 pounds each) and install new coils, the 13-ton magnet and frame had to be moved from its normal vertical position on a rotating carriage to a horizontal position on the floor. This required special fixtures, rigging, cribbing, and cutting of the rotating carriage framework.

Following installation of new coils, the magnet was calibrated with beam, employing the time-of-flight method developed for a previous calibration.[2] The calibration procedure consists of a series of measurements of absolute beam energy as a function of NMR magnetic field reading over the excitation range of the magnet. The energy calibration had changed less than 2% overall and less than 1% below $E_0 = 250$. A third-order polynomial fitted to the data is the following:

$$K = 1.34165 + 0.2888 \times 10^{-4}\, E0 - 0.20831 \times 10^{-6}\, E0^2 + 0.11916 \times 10^{-8}\, E0^3$$

where K, the ratio of relativistically-correct mass-energy product, E_0, to the square of the measured magnetic field, is used to calculate the NMR reading for a desired E_0. Use of this equation is believed to give an analyzed beam energy accurate to at least $\pm 0.1\%$.

1. M. R. Dinehart et al., *Phys. Div. Prog. Rep., Sept. 30, 1994, ORNL-6842* (1994), p. 1-8.
2. D. K. Olsen, K. A. Erb, C. M. Jones, W. T. Milner, D. C. Weisser, and N. F. Ziegler, *Nucl. Instrum. Meth. Phys. Res. A* **254**, 1 (1987).

TANDEM ACCELERATOR RADIATION SAFETY SYSTEM UPGRADE

R. C. Juras, J. L. Blankenship, S. W. Mosko

The tandem accelerator radiation safety system was upgraded for three reasons: (1) to comply with DOE Order 5480.25 and ORNL FS 4.1, (2) to improve system electrometers, and (3) to extend the system to the new RMS experimental area.

When the new safety orders went into effect, the tandem accelerator radiation safety system was reviewed and a number of corrective actions identified to bring the system into compliance. Corrective actions ranged from changing all magenta beacons to red beacons, which are appropriate for the range of possible radiation dose rates in the tandem accelerator areas, to installing redundant beacons, horns, and electronic circuits.

Although not required by the safety orders, all system electrometers were upgraded at the same time. There were two primary motivations for the upgrade: (1) to replace old electrometer circuitry which was based on obsolete modules and circuits, the most troublesome of which was the Analog Devices AD311K electrometer module which is no longer available, and (2) to greatly improve internal self-diagnostics. In the new design, internal power supply failure or a disconnected cable results in control room alarms and insertion of a beam stop.

The system was extended to the new RMS area to provide the convenience of a permissive entry system to RMS experimenters. Specifically, as in other accessible tandem accelerator areas, the radiation level is continuously integrated; the tandem accelerator is shut down if integrated dose exceeds 20 mrem or if the dose rate exceeds 150 mrem/h.

WATER COOLING SYSTEM FOR TANDEM INJECTOR

G. D. Mills and Y. S. Kwon[1]

The tandem injector was installed in the late 1970s with a recirculating cooling system to remove heat from the walls of the ion source vacuum chamber, the sputter cathode, and the ion source turbopump. Freon 113 was the heat exchange medium of choice due to its high electrical resistivity. This allowed the mechanical components of the recirculating system to be mounted at ground potential with nylon hoses carrying the freon across the 7 ft. gap to the nominal 500-kV ion source platform. Although this system continued to work well, motivation to change came from the decreasing availability of Freon 113 driven by environmental concerns of depletion of atmospheric ozone. Environmentally acceptable freon substitutes such as Freon 141b at a cost of $2,000/50 gal. barrel provided an economically unsuitable option .

The alternative we chose was a recirculating water-cooled system with a liquid-to-air heat exchanger as shown in Fig 1.2. Water is economical, environmentally acceptable, and compatible with the stainless steel, aluminum, and nylon parts of the flow path. All components of the system are installed in the limited space on the ion source platform to avoid the current drain across the 500-kV acceleration voltage. The reservoir was filled and after two days of circulation through the on-line mixed resin deionizer, the resistivity of the water stabilized at 14 mega-ohm/cm. Local interlocks for equipment safety are installed for the water level in the reservoir and over-temperature protection for the pump. Remote readouts in the control room are planned for the water level in the reservoir, water flow, and resistivity. Negative-ion beams produced from the injector have shown stable performance with the new cooling system in operation.

1. ORNL Plant and Equipment Division.

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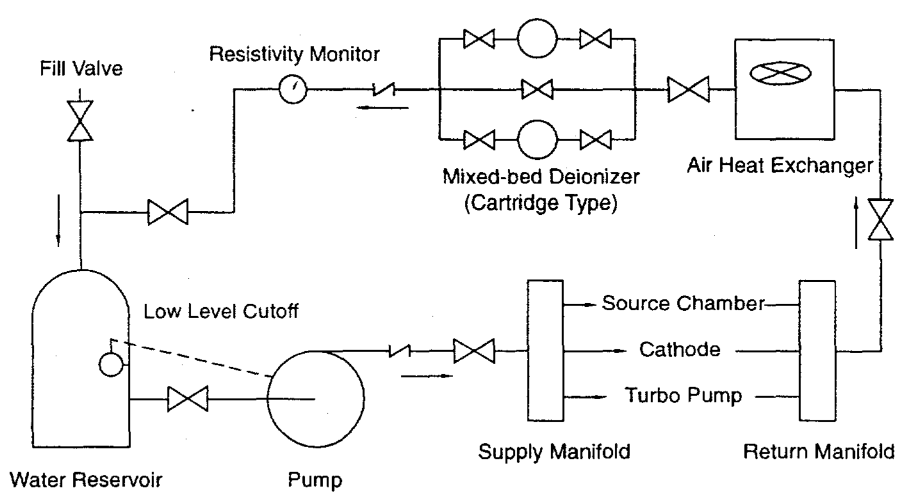

Fig. 1.2. Recirculating water-cooled system.

TANDEM CONTROL SYSTEM UPGRADE

R. C. Juras, M. J. Meigs, J. W. Sinclair

The tandem accelerator control system has been remarkably reliable and effective since the beginning of tandem accelerator operation in 1982, but control system software is highly dependent on the 1970's-vintage Interdata/Perkin-Elmer/Concurrent control computers, and the computers cannot be maintained much longer. Unfortunately, there is no viable upgrade path; control system software is written largely in assembly language closely tied to the operation of one-of-a-kind direct memory access (DMA) hardware.

A new system which replaces the control computers and system software has been procured. The system is based on toolkit software (Vsystem) available from Vista Controls and real-time front-end software (VxWorks) from Wind River. Hardware consists of a DEC Alpha, a VME-based Heurikon computer, and a Kinetics Systems 2917/3922 link to CAMAC. Ethernet links the DEC Alpha, the Heurikon VME computer, and operator X-terminals.

Hardware integration is straightforward. All tandem accelerator controls are based on CAMAC. All communications to CAMAC originate from two CAMAC crates containing Kinetic System 3992 serial highway drivers. A simple link from VME to the two originating CAMAC crates is all that is required. Software integration is more involved; CAMAC handler software, conversion routines, initialization, failure/recovery, alarm manager, parameter save/restore, and tandem accelerator utility routines must be either developed or ported from the old computers.

The new system is under development and will be ready for test by early spring 1997. Testing of the system will be coordinated with regular tandem accelerator maintenance periods.

RIB INJECTOR OPERATIONS

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On August 30, 1996, the HRIBF successfully accelerated its first radioactive ion beam. The initial demonstration beam was ^{70}As, produced in the ^{70}Ge (p,n) reaction using 42-MeV protons from ORIC on a liquid germanium target and accelerated to 140 MeV by the 25-MV tandem accelerator. The demonstration was carried out under the rules for low-intensity commissioning which limited the driver proton beam to approximately 100 nA. Unfortunately, the actual proton intensity incident on the production target was only 10 nA during the demonstration as a result of various difficulties with ion-optical and diagnostic equipment on the beam line from ORIC. Consequently, the accelerated ^{70}As beam current was very low (2000 ions/s), but easily detected by observing gamma radiation following beta decay. This would correspond to an accelerated beam current of 10^6 ions-per-second-per-microampere of proton beam, under production conditions using an enriched ^{70}Ge target. A natural (20% ^{70}Ge) target was used in the demonstration run. A beam of ^{69}As was also produced, accelerated off the RIB injector platform, accumulated on a moving tape system, and detected by observing its decay.

We have made great progress in understanding and optimizing the performance of the RIB injector. We can now routinely ensure that the beam coming from the ion source via the extract electrode is on the optical axis of the RIB injector. This is done by using the first two of the four electrostatic quadrupoles immediately after the ion source as steerers (i.e., pure dipoles, no quadrupole strength). The first steerer bends the beam so that it crosses the optical axis at the position of the second steerer. The second steerer bends the beam parallel to the optical axis.

During preparation for the demonstration run, we observed a total transmission of 28% for ^{70}Ge ions through the injector system from the ion source to the tandem accelerator. Essentially all loss was in the Cs vapor charge-exchange cell; transmission of positive ions through the cell with no Cs vapor was 70% and the measured negative ion fraction was 40% under demonstration run conditions. All other elements, including the second-stage mass separator, transmitted the beam without measurable loss. These measurements were made with a 50-keV ^{70}Ge beam on the high-voltage platform, accelerated to 200 keV for second-stage analysis, and injected into the tandem. The transmission of the entire system from the ion source through the tandem was measured to be about 6%, corresponding to a transmission through the tandem itself of 20%.

The design mass resolution of the second-stage mass separator is 1 part in 20,000. The resolution is limited by the size of the beam at the object of the separator in the dimension corresponding to the bending plane of the separator. We achieved 100% transmission with a beam size corresponding to a resolution of 1 part in 7500 (FWHM). No effort was expended to tune for a smaller spot. With this tune, we could achieve 1 part in 10,000 resolution with 60% transmission or 1 part in 20,000 with approximately 20% transmission.

During the past year, several engineering modifications have been made to the RIB injector. All air and water valves associated with the target-ion source have been moved to the instrumentation platform in C111N. The extract electrode drive mechanism has been moved to the top of the Faraday cage in C111S to minimize radiation damage to the drive motor and associated limit switches. Flexible spring mounts have been installed on the extract electrode to allow easier movement. The self-sealing features of the water connections to the target-ion source have been removed to improve reliability of cooling water flow. The air actuated hold-down clamps for the target-ion source base plate have been replaced with a more robust cantilevered-roller clamping system. The positioning pin arrangement for the target-ion source base plate and table has been modified to accommodate the Remote Handling System. All elastomer O-rings in the extraction region have been replaced with metal O-rings. The acrylic supports for the deceleration tube and for the extraction area ceramic insulators have both been replaced with radiation-resistant G-10 supports.

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REMOTE HANDLING SYSTEM

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The Remote Handling System (RHS) for the Holifield Radioactive Ion Beam Facility (HRIBF) was installed by PaR SYSTEMS, Inc. of Shoreview, Minnesota, during March 1996.

The RHS consists of three major components: (1) a robotic arm that is mounted on the 300-kV source platform next to the Target-Ion Source (TIS); (2) a conveyor that extends from the source platform room (C111-S) through the cyclotron vault (C109), and into a shielded storage room (C110); and (3) a robotic gantry crane in C110.

The robotic arm (GALILEO) is a PaR Model 6350 Telerobotic Manipulator which has six degrees of freedom (the human arm has seven degrees of freedom). GALILEO is driven by electric motors and steel reinforced polyurethane belts. GALILEO is designed to withstand 10^8 rad total dose and, with periodic replacement of the motors and belts, 10^9 RAD total dose.

The RHS will only operate when there is no cyclotron beam and when there is no high voltage. The TIS will remotely disengage from the Radioactive Ion Beam (RIB) Injector vacuum system and move to a retracted fiducial position on the 60-kV table. GALILEO will pick the TIS up and place it in a stainless steel Contamination Control Box (CCB) which will sit on the end of the conveyor which will temporarily extend into the gap between the source platform and the C111-S wall. GALILEO will then put a dust-tight cover on the CCB. The end of the conveyer and the CCB will retract into the wall and the motor-driven rollers of the conveyor will move the CCB through C109 and into C110. In C110, the robotic gantry crane (PICASSO) will pick the CCB up off the conveyor and place it inside a lead cask. PICASSO will then put a lead lid on top of the cask. The RHS will also reverse this sequence to install a new TIS on the RIB Injector.

The RHS successfully performed 50 consecutive repetitions of moving a 250 lb TIS mock-up (twice the weight of a nominal TIS) from the cask position in C110 to the fiducial position on the 60-kV table and then back again to the cask position. Each repetition took 41 minutes to complete. The RHS performed all 50 repetitions over a 34-hour period without any human intervention.

The PaR SYSTEMS, Inc.-supplied control system for the RHS is fully programmable and includes manual options for both GALILEO and PICASSO. The RHS control system will communicate with the RIB Injector VISTA-based control system.

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FACILITY MODIFICATIONS

D. T. Dowling, Y. S. Kwon,[1] *S. W. Mosko, B. A. Tatum*

Shielding Reconfiguration

Several shielding wall modifications were made in the cyclotron vault (room C-109). Openings were arranged through the shielding walls to rooms C-111S and C-110 to accommodate a remote handling system for activated target-ion sources. A portion of that system is a conveyor which passes through C-109 and transports ion sources between robotic handlers in the adjacent rooms. This work involved removal of stacked concrete blocks and beam line components that are no longer in use.

The beam line passage on the south end of the cyclotron vault that formerly was used for transporting ORIC beams to rooms C112, C113, C114, and for transporting tandem beams to rooms C110, C113, C114, was reconfigured as part of C114. The ORIC beam lines were removed from the south end of room C109 and the opening to the beam passage area was sealed with concrete blocks. Access to the beam passage is now available through room C114.

The ORIC radiation safety system was revised to accommodate the reconfiguration of rooms C109, C110, C111N, and C111S. Since there are shield wall openings between all of these areas, they are now treated as a single entity. Thus, all four rooms must be cleared of personnel and sealed before cyclotron operation can be permitted.

Rooms C113, Spin Spectrometer, and C114, UNISOR, are now operated as part of the tandem radiation safety system. The new room C116, RMS, area is also treated as part of the tandem radiation safety system. Room C112, the former transuranium experiment area, is presently inactive and not part of the radiation safety system.

Auxiliary Cooling Tower Installation

An auxiliary evaporative water cooling tower was installed on the roof of the 3rd floor equipment room. This tower serves as an alternative cooler for the condenser on the "South Chiller" in the building HVAC system. The South Chiller normally provides chilled water for air conditioning to all tower rooms and the tandem accelerator's cooling system. It also provides cooling for the main building through the "cross-tie heat-exchanger." The auxiliary cooling tower is intended to operate during cool weather (less than 20°C) when neither ORIC nor the north chiller is operating. At such times, the facility's main cooling tower will be shut down with a resultant saving of about $40,000 in annual electric power expenses. Some additional process cooling is derived by passing process water through a water-to-air heat exchanger in the building HVAC air intake system.

Utilities Upgrades

A dechlorinator system was added to the facility's process water drain. This system collects coolant water from all equipment that uses process water (potable water that has been isolated via backflow preventer) and removes chlorine before release to White Oak Creek.

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1. ORNL Plant and Equipment Division.

BEAM LINE 14

D. T. Dowling, B. A. Tatum

A new beam line, designated Beam Line 14, has been designed, built, tested, and commissioned. Beam Line 14 transports beam from Tandem Beam Line 31 to the recently commissioned Recoil Mass Spectrometer (RMS) at the Holifield Radioactive Ion Beam Facility (HRIBF). The design of the beam line utilized existing components where possible to reduce the overall cost. Several existing beam lines were decommissioned as part of the construction of the HRIBF, resulting in the availability of several major beam line components such as quadrupoles, steering magnets, diagnostic actuators, diagnostic chambers, beam line valves, pump station valves, cryopumps, and alignment fixtures. The use of existing components saved in excess of $200K in purchased equipment. Existing utility services in the beam transport room did not have adequate capacity to handle the added load of the new beam line. Therefore, new utility services, including compressed air, demineralized water, process water, and electrical power distribution, were installed. New shielding was installed and existing shielding was reconfigured to provide optimum use of existing space and to provide improved access to beam transport rooms.

The beam line consists of four major optics components: two quadrupole doublets provide the proper beam shape capabilities at the RMS target station, and two 15° dipoles change the elevation of the beam line from the nominal beam line height of 48 inches to the RMS target station height of 81 inches. A beam which is properly tuned before entering Beam Line 14 and which has a double focus at the second viewer will form a beam spot at the RMS target which is typically 2.5 mm high and less than 1 mm wide. There are two diagnostic areas, each consisting of a beam viewer, a Faraday cup, and a beam profile monitor. The beam line is constructed of stainless steel components utilizing "Conflat" seal flanges. The vacuum pumping is accomplished by four 1500 L/s (N_2) cryopumps which provide a beam line base pressure of less than 5E-8 Torr.

The control and status feedback of all components on the beam line are provided through the VISTA distributed control system utilizing programmable logic controllers (PLCs) and a VME serial interface to vacuum gauge controllers. The PLC communicates with VISTA through an ethernet connection and can be located anywhere the ethernet is available. The ethernet was, therefore, extended to the beam transport hall and the PLC, vacuum instrumentation, and power supplies were installed in instrumentation racks adjacent to the beam line. This resulted in simplified wiring localized to the beam transport room, reduced installation costs, and simplified troubleshooting. The beam profile monitors were tied to the existing multi-trace BPM system used on tandem beam lines. This system provides the operator with multiple BPM traces on a single scope resulting in better beam diagnostic capability. The existing camera system was extended to accommodate cameras which monitor the beam viewers.

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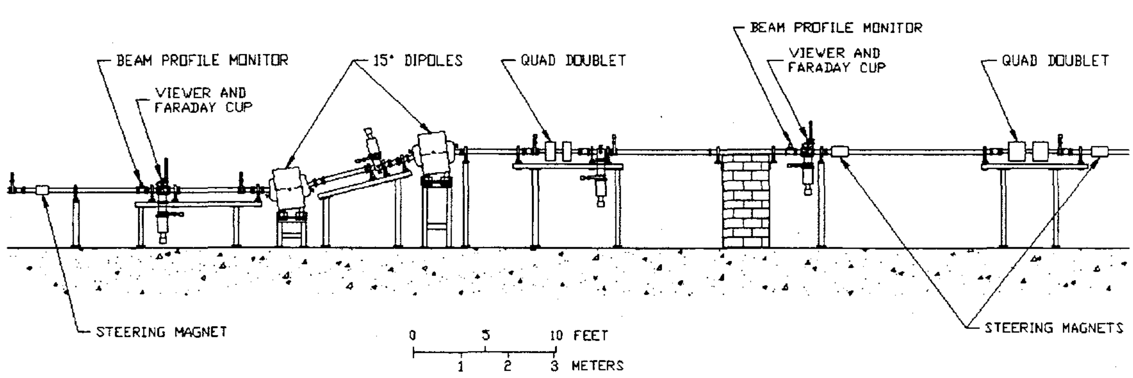

Fig. 1.3. Beam Line 14.

LOW INTENSITY BEAM IMAGING – POSITION SENSITIVE AVALANCHE COUNTER

T. A. Lewis,[1] D. Shapira

The purpose of this device is to aid the accelerator operator in steering and focusing the beam on its way from the exit of the accelerator to the experiment target. It can also serve to view and integrate the incident beam at the experiment target where standard methods have proven inadequate at very low beam intensities. While this device is mostly intended for the lowest intensity beams, it should be useful up to intensities of 10^6 particles/s. With a perforated (10% transmission) plate in front, one may be able to increase this number further.

A schematic diagram of the detector is shown in Fig. 1.4. The avalanche signal in a four Torr isobutane environment is picked up by sense wires (spaced one millimeter apart on each of two position planes) which are attached to delay line taps and propagated to each end of the delay line chain with a delay which is determined by the wire position. The difference in the time of arrival of these two signals is then typically processed by a time-to-amplitude converter then digitized and presented to a computer for analysis and display. It is also possible to display the signals from the time-to-amplitude converters on a storage oscilloscope in X-Y mode.

Improvements were made in the voltage hold-off capability and in the quality of the signal from the avalanche by optimizing the plane spacing, the gas flow path, and the reduction of sharp points. Position and resolution calibration tests performed with alpha-particles showed good position linearity and resolution of at least one millimeter.

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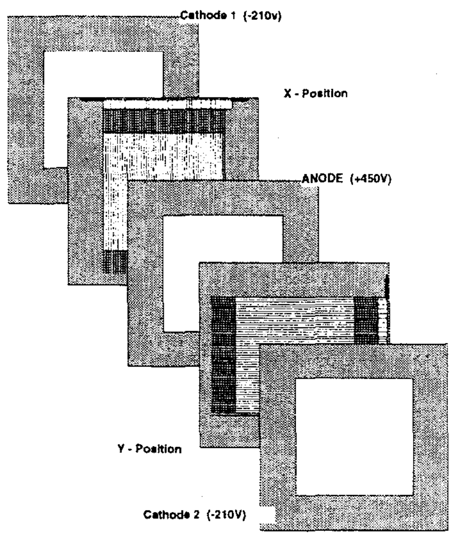

Fig. 1.4. A double position sensitive PSAC exploded view - anode and cathode are thin conducting foils, sire planes or wire mesh.

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BEAM IMAGING WITH CCD CAMERA AND PHOSPHORUS MATERIAL

N. Gan,[1] *D. Shapira*

One of the simplest options of beam imaging is to look directly at images of beam produced by the fluorescent light of phosphorescent materials. The availability of commercial CCD cameras with high sensitivity and low price makes this option very cost-effective. We have performed an in-beam test with a CCD camera and various phosphorus materials.

A test station has been assembled and put at the end of the beam line 23. The layout of this station is presented in Fig. 1.5. The phosphorescent materials were Y_2O_2S:Eu, Gd_2O_2S:Tb, G:Ce[2] and Al_2O_3. Two tests have been done; one was 120 MeV $^{32}S(7+)$ on Y_2O_2S:Eu and Al_2O_3; the other was 60 MeV $^{16}O(3+)$ beam on Y_2O_2S:Eu, Gd_2O_2S:Tb, YAG:Ce and Al_2O_3.

During the experiment, the counting rates were monitored by a plastic scintillator with a photomultiplier. The fluorescent image of the beam on the phosphorus target was viewed by a CCD camera and recorded by a VCR video recorder. For both tests, the beam images were clearly seen on the Y_2O_2S: Eu, Gd_2O_2S:Tb and YAG:Ce at counting rate as low as 3000 – 4000 cps. For the alumina, the beam image was barely seen at 3000 cps.

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2. Hollerman, et al., *IEEE Transactions on Nuclear Science* **38**, No. 2, 184 (1991).

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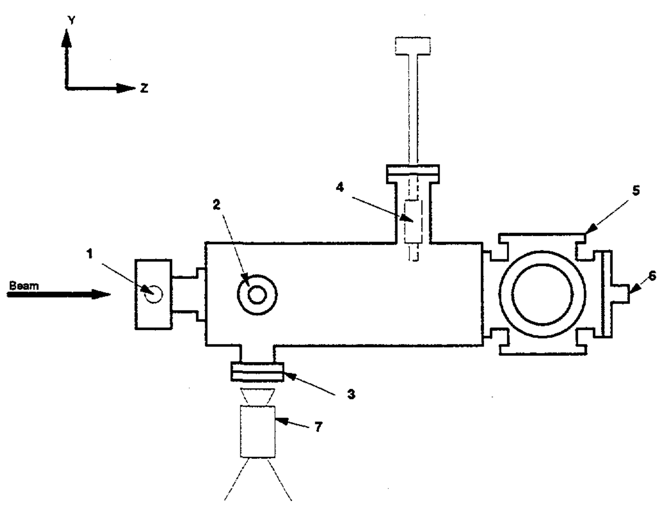

Figure 1.5. The test station for beam profiling devices: (1) The quartz viewer. (2) The phosphorus targets. (3) and (7) The CCD camera. (4) The plastic scintillator and photomultiplier detector. (5) The general purpose port. (6) The Faraday cup.

OAK RIDGE ELECTRON LINEAR ACCELERATOR (ORELA)

D. C. Larson, K. H. Guber,[1] T. A. Lewis[2]

ORELA is an intense, pulsed, high intensity neutron source used for basic research in nuclear astrophysics and fundamental properties of the neutron. In addition, ORELA hosts a pulsed, intense photon source and slow positron source. It is an ORNL User Facility, and as such is available, on a cost recovery basis, for work requiring neutrons, photons, or positrons. ORELA now operates about 1200 hrs/year. The charge rates for accelerator use have been reviewed and modified. A Scientific Liaison for non-Physics Division research at ORELA has been appointed, and work for the Defense Nuclear Facility Safety Board and the National Spallation Neutron Source has been initiated.

Measurements of importance to nuclear astrophysics completed since October 1994 include total and capture cross sections on isotopic samples of ^{134,136}Ba, ^{142,144}Nd, ^{116,120}Sn, and a measurement of the ^{7}Li(n,γ) cross section. A precision measurement of the total cross section of ^{208}Pb was done for additional improvements to the value of the neutron polarizability. The physics resulting from these measurements is discussed elsewhere in this report.

The pulsed, intense photon source at ORELA continues to be used by a local, small business under an SBIR grant. Two pulses each second are diverted from the electron beam, and strike a tantalum converter which produces an intense photon pulse. The associated neutrons are stopped in a water trap behind the converter, and the remaining electrons are bent away by a magnet in the water trap. The resulting beam has a photon/neutron ratio of 2500/1. This beam is used for semiconductor materials modification, and results describing recent research on silicon detectors has been published.

In addition to the intense neutron and photon sources, ORELA also hosts the most intense pulsed positron source in the U.S., funded through DOE/BES and at no cost to DOE/NP. It utilizes remaining beam passing through the neutron-producing target to strike a tantalum radiator, in which positrons are produced and transported to an experimental area for use as a probe in materials research. A flux of 10^8 slow positrons/second is available, and design work is complete to equip the positron beam line with a buncher, which will allow positron lifetime spectroscopy measurements. Recent results include evidence for the formation of positronium hydroxide and positronium chloride has been seen, and ionization of rare gases below the sub-positronium threshold has been observed.

Safe and efficient operation of the accelerator and associated facility have also been addressed in this time frame. Numerous reviews of several aspects of facility operation have occurred, with positive findings from each review. ORELA has recently been classified as a Routinely Accepted facility, and modifications to our Facility Authorization Basis Documents are under way to reflect these changes. Training and Procedure documents are also under revision.

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SAFETY DOCUMENTATION

D. K. Olsen and C. M. Jones

In addition to the usual "background" safety documentation and review activity associated with normal operation of the HRIBF, substantial progress has been made toward receiving authorization for routine operation. This authorization, paralleling the development of the facility, was divided into three steps: Low-intensity commissioning, high-intensity commissioning, and routine operation. This contribution briefly describes the principal efforts toward receiving authorization for these steps. The HRIBF was designated on August 9, 1994, as a low-hazard facility by DOE Headquarters, based on the HRIBF Hazard Screening (HS/6000/F/1/R1). The Safety Assessment, SA (SA/6000-PHYS/PHYS/R1) and Accelerator Safety Envelope, ASE (ASE/6000-PHYS/PHYS/R1) for Low-Intensity Commissioning were approved by the DOE Site Office on October 14, 1994. The SA addresses safety-related issues associated with modifications to the facility, with respect to the original 1982 Final Safety Analysis Report for Heavy Ion Facility (ORNL/CF-81/330). The ASE provides the limiting conditions of operation and replaces the original Operating Safety Requirements for Heavy Ion Facility (ORNL/CF-81/331) document that had been in use since 1982.

An Accelerator Readiness Review, ARR, for low-intensity commissioning, based on these SA and ASE documents, was conducted by the ORNL Accelerator Safety Review Committee on October 4-5, 1994. This review addressed the adequacy of preparations for low-intensity commissioning of the facility. Authorization to commence low-intensity commissioning was granted by the Site Office on November 23, 1994.

In August of 1995, the ASE for Low-Intensity Commissioning was revised to allow modifications to room C110 in order to install the remote handling system for activated target-ion sources. This revision (ASE/6000-PHYS/PHYS/R2) was approved by the DOE Site Office on August 29, 1995. This ASE and the SA for Low-Intensity Commissioning, along with the original 1982 Final Safety Analysis Report and 1994 HRIBF Hazard Screening, constitute the present facility authorization basis.

In October of 1995, the SA (SA/6000/HIC-PHYS/R1) and ASE (ASE/6000/HIC-PHYS/R1) for High-Intensity Commissioning were completed. These documents were approved by the DOE Site Office on October 23, 1995.

In August of 1996, the Safety Assessment (SA/6000/RO-PHYS/R0) and Accelerator Safety Envelope (ASE/6000/RO-PHYS/R0) for Routine Operation were completed. This safety assessment is a stand-alone document and will retire the original 1982 Final Safety Analysis Report which will then only serve as a reference document. These routine operation documents were approved by the DOE Site Office on October 31, 1996.

Much of the preparation for an Accelerator Readiness Review seeking authorization for both high-intensity commissioning and routine operation has been completed. This final ARR is scheduled for December of 1996 and should complete the process of authorization for routine operation. Among the major activities completed in preparation for this ARR have been the organization of the HRIBF staff training records and the completion by the staff of the HRIBF-specific, in-house training. Another major activity has been the completion of hardware changes to enhance the facility radiation safety systems. These enhancements were required as part of the HRIBF Implementation Plan for DOE Order 5480.25.

TARGET AND ION SOURCE RESEARCH AND DEVELOPMENT

PROGRESS IN THE DEVELOPMENT OF TARGETS AND ION SOURCES FOR THE HRIBF RESEARCH PROGRAM

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The objectives of the target/ion source development program are to provide advanced and innovative targets and positive/negative ion sources that, in combination, are capable of providing a wide variety of proton rich radio-nuclei at the intensities required for use in nuclear structure and astrophysics research programs at the HRIBF. In order to be successful in the near-term and in the future of our facility, several difficult and challenging problems **must** be solved in each of the two arenas. We are aggressively developing both targets and ion sources with the unique characteristics necessary to overcome specific and general problems that plague RIB generation. There are no universal target materials or ion sources that meet the fast release and efficiency criteria for a wide range of RIB species as required for successful operation of a RIB facility. In general, each RIB species must be considered separately because of the diversity in the chemical, metallurgical, and physical properties of the elements. We have identified the major problems associated with RIB generation that lay as obstacles in the path to success and are aggressively seeking solutions to these problems through the development of novel "on-line" ion sources and target concepts. In this Progress Report, we summarize our efforts over the past two years toward reaching these objectives.

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5. Consultant, Gilbert/Commonwealth Engineering Consultants, Oak Ridge, TN.

6. ORNL postdoctoral associate/ORAU.

ADVANCED TARGET CONCEPTS FOR RIB GENERATION

G. D. Alton

In order to successfully perform nuclear structure physics and nuclear astrophysics research with radioactive ion beams (RIBs), intensities ranging from 10^5 to 10^{10} particles/s must be delivered to the experimental station. While these intensities appear modest, they are not easily achievable because of the limited production rates of the species and their lifetimes in relation to the times required for diffusion from solid state targets and effusion into the ion source. During this reporting period, we have made progress toward designing advanced composite target-matrix/heat-sink systems that simultaneously incorporate the short diffusion lengths, high permeabilities, controllable-temperatures and heat removal properties necessary to effect maximum diffusion release rates of short-lived, radioactive species as required for efficient radioactive ion beam (RIB) generation in nuclear physics and astrophysics research programs. The target materials may be used directly as small diameter particulates coated or uncoated with Re or Ir to minimize adsorption following diffusion release and eliminate sintering of the particulates at elevated temperatures; plated onto both sides of thin disks (for example, disks of carbon) or plated, in thin layers, onto low density carbon-bonded-carbon-fiber (CBCF) or reticulated-vitreous-carbon-fiber (RVCF) coated with Ir or Re to form sponge-like composite target matrices; or in other cases, where applicable, the target material of interest can be grown in crystalline fibrous form and fabricated in woven mats of the target material to form a highly permeable structure. Figure 1.6 displays a scanning electron microscope (SEM) photograph of Ni coated RVCF for the production and release of the isotopes of Cu and Fig. 1.7 displays a SEM of a woven mat of an Al_2O_3 fibrous target that has been successfully used to release $^{17,18}F$ for the first time.[1]

ORNL-DWG. 96M-7518

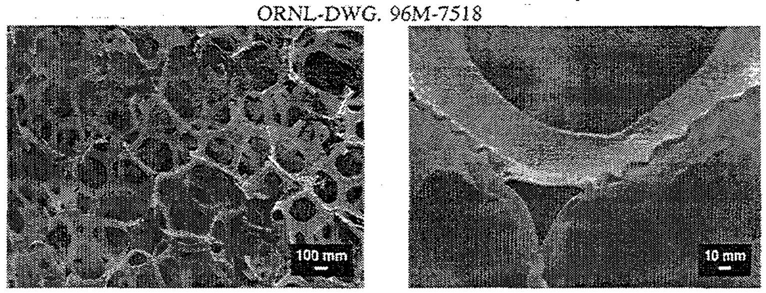

Fig. 1.6. A scanning electron miscroscope (SEM) photograph of reticulated-vitreous-carbon-fiber (RVCF) (density: ~0.06 gm/cm^3) electroplated with Ni metal for potential use in generating RIBs of the isotopes of Cu.

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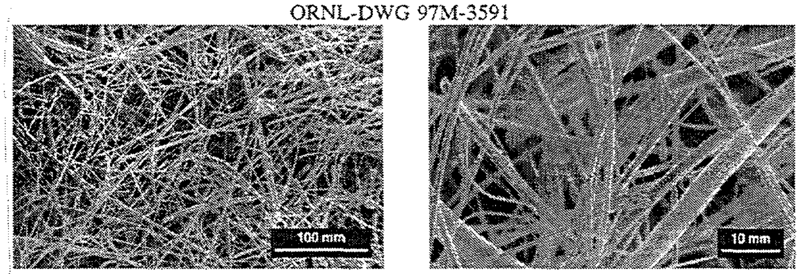

Fig. 1.7. A scanning electron miscroscope (SEM) photograph of an Al_2O_3 fibrous matrix (fiber diameter: 3 μm) which has been successfully used for low intensity, "on-line" production and release of $^{17,18}F$ as a means for possible use in generating RIBs of the isotopes of Cu.

1. D. Stracener, H. K. Carter, J. Kormicki, J. C. Blackmon, M. S. Smith, and D. W. Bardayan, in *Proceedings of the International Conference on Applications of Accelerators in Research and Industry* (to be published).

COMPUTATIONAL DESIGN OF HIGHLY PERMEABLE, COMPOSITE-TARGET-MATRIX/HEAT-SINK SYSTEMS

G. D. Alton and J. W. Middleton[1]

In order to meet the intensity and species needs for nuclear physics and astrophysics research with radioactive ion beams (RIB)s, targets must be developed that simultaneously incorporate the short diffusion lengths, high permeabilities, controllable-temperatures and heat removal properties required to effect maximum diffusion release rates of short-lived, radioactive species produced in nuclear reactions between high-energy-light ion beams and specific nuclei. We have chosen low-density matrixes for this purpose, such as carbon-bonded-carbon fiber (CBCF) or reticulated-vitreous-carbon fiber (RVCF) to serve as the target material plating matrix and thermal transport conduit for heat removal. Since short-lived particles must swiftly diffuse from the target material, the diffusion lengths must be short (thin target materials), and the target temperature must be as high as practicable. During this reporting period, several computer codes were used to simulate generation and removal of heat, deposited during light ion beam irradiation of the target matrix. For example, heat generation is simulated with the Stopping and Range of Ions in Matter (SRIM[2]); the finite element computer code ANSYS[3] is used to simulate the heat transport from the target through the beam-stop and to the heat-sink; and the finite element FLOTRAN[4] is used to compute the coefficient of heat transfer across the Cu/H_2O heat-sink interface. We have used the codes to design Al_2O_3/Ir/RVCF targets for the production of the isotopes of F; Ni/RVCF targets for production of the isotopes of Cu; CeS macroparticle targets for the production of Cl isotopes; and UC/Ir/RVCF targets for the production of fission product radionuclei. These codes can be used to determine the maximum power that can be deposited in the target without compromising the ionization efficiency of the source or the integrity of the target itself. Comparisons of the radial and longitudinal temperature profiles with and without pyrocarbon on the face of the beam stop are displayed in Figs. 1.8 and 1.9 for Al_2O_3/Ir/RVCF. The pyrocarbon is used as a thermal barrier to reduce the longitudinal and radial temperature gradients in the composite target.

1. Graduate student, Mississippi State University, Starkville.
2. SCRIM - The Stopping and Range of Ions in Matter, J. R. Ziegler, IBM Research, Yorktown Heights, NY.
3. ANSYS is a finite element computer code designed to solve thermal conductivity and thermal transport problems; the code is a product of Swanson Analysis Systems, Inc., Houston PA.
4. FLOTRAN is a finite element code for calculating heat transfer coefficients between media interfaces; the code is a product of Swanson Analysis Systems, Inc., Houston, PA.

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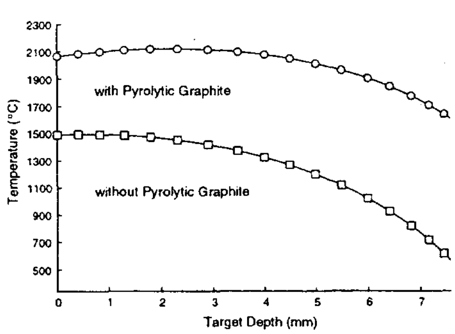

Fig. 1.8. Centerline temperature distribution along the axis of an Al_2O_3/Ir/CBCF composite target bonded to a C beam stop, with and without pyrocarbon at the interface of the composite target and beam stop. The target is a candidate form production of the isotopes of F.

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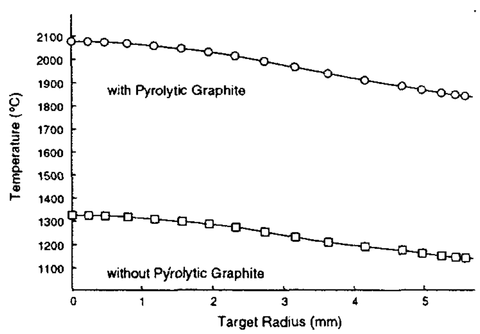

Fig. 1.9. Radial temperature distribution at the mid point of the Al_2O_3/Ir/CBCF composite bonded to a C beam stop, with and without pyrocarbon at the interface between th and beam stop. The target is a candidate form production of the isotopes of F.

SECOND GENERATION ELECTRON BEAM PLASMA TARGET/ION SOURCE

G. D. Alton, G. D. Mills, C. Williams[1]

After determining that all of the mechanical problems, uncovered during operation of the original CERN-ISOLDE type EBPIS had been solved, and as a consequence of the high degree of reliability, excellent performance and ruggedness of the improved EBPIS previously described in this report, a decision was made to build a simplified, low cost version of the source for potential use as the principal "on-line" RIB source. This source, shown schematically in Fig. 1.10, has been fabricated and will be tested in the near future. We have used the code described in Ref. [2] to iteratively design the extraction electrode boundary. The angular divergences of extracted beams are found to be reduced by factors of ~2 compared to those obtained from the original CERN-ISOLDE type EBPIS by extracting from a hemispherical focus electrode boundary. This electrode design will be used in all EBPTISs and surface ionization sources where appropriate.

1. Consultant, Gilbert/Commonwealth Engineering Consultants, Oak Ridge, TN.
2. PBGUN, Thunderbird Simulations, Garland, TX.

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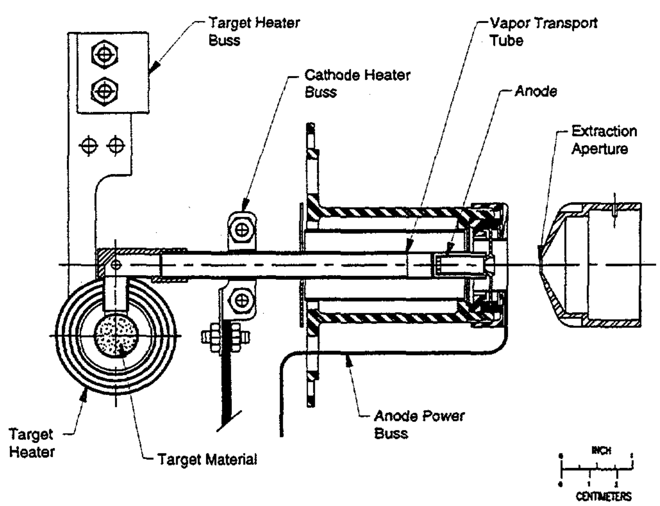

Fig. 1.10. Schematic drawing of a low cost, simplified EBPIS for potential use on-line for RIB generation. The source embodies the same engineering features as the improved EBPTIS described previously in this report.

A COMBINATION THERMAL DISSOCIATION/ELECTRON IMPACT IONIZATION SOURCE FOR RIB GENERATION

G. D. Alton, B. Cui,[1] R. F. Welton,[2] J. W. Middleton,[3] C. Williams[4]

Chemically active RIB species, diffused from the target material, often arrive at the ionization chamber of the source in a variety of molecular forms. Because of the low probability of simultaneously dissociating and efficiently ionizing the individual atomic constituents of molecules containing the element of interest with conventional hot-cathode electron-impact ion sources, the species of interest are often distributed in several mass channels in the form of molecular sideband beams. In this way, the beam intensity of the species of interest is diluted. We have conceived an ion source that combines the excellent molecular dissociation properties of a thermal dissociator and the high efficiency characteristics of an electron impact ionization source for ionizing atomic species to address these problems. The source, shown schematically in Fig. 1.11, was specifically designed for potential use in generating RIBs at the HRIBF. Radioactive species diffused from the high temperature target will be transported through the resistively-heated W vapor transport tube maintained at thermonic emission temperatures (~ 2200°C) and into the solid region of the positively biased W tube and which is heated to ~ 2500°C by acceleration of electrons emitted from the inner surface of the cathode/vapor transport tube. The vapor entrance end of the anode is solid; it is followed by a section with slots in the sides of the anode near the ion extraction end of the anode. The first part of the tube serves as the thermal dissociator while the second part of the tube allows electrons to bombard the dissociated molecular atomic constituents to generate atomic ions which then are extracted from the tube to form the RIB beam. The ion optics of the source are identical to those of the second generation EBPIS, displayed in Fig. 1.10.

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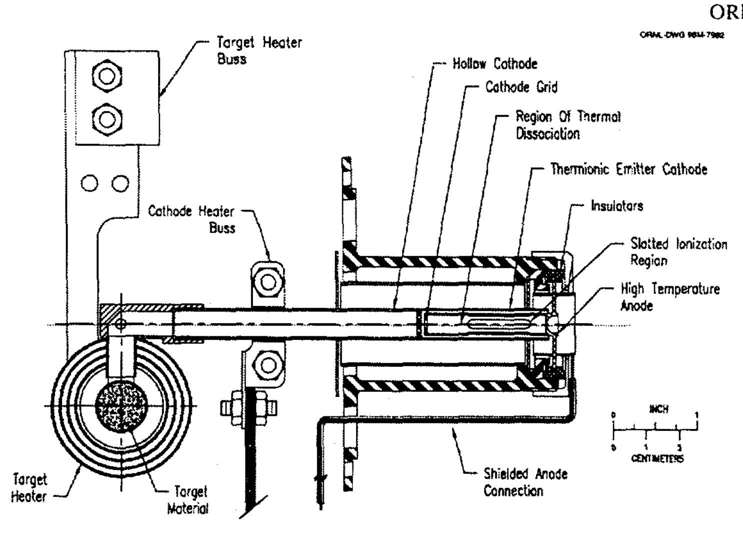

Fig. 1.11. Schematic drawing of the combined thermal dissociator/electron impact ionization source concept for use in sequential dissociation of molecular and electron transport ionization of their atomic constituents. The source will be complementary to the electron impact ionization sources described in this report.

A DIRECT EXTRACTION NEGATIVE ION SOURCE FOR RIB GENERATION

G. D. Alton, R. F. Welton,[1] B. Cui,[2] S. N. Murray

Radioactive beams of ^{17}F and ^{18}F are among the first beams planned for use in the HRIBF astrophysics research program. We have conceived, and evaluated a direct-extraction electron-impact ion source for use in generating beams of F^-, Cl^- or highly electronegative species. The source displayed in Fig. 1.12, is based on operation of the second iteration EBPTIS in the negative mode with provisions for introducing Cs vapor from an external oven into the discharge which enhances negative ion formation efficiency by several orders of magnitude. This additional mode of operation greatly increases the versatility of the EBPIS for many HRIBF applications. Functional dependencies of F^- beam yield were measured against Cs flow-rate, F flow-rate, F carrier species, electron beam energy, electron beam current, and confining magnetic field strength. Ionization efficiencies of ~ 0.1% and delay times of ~ 30 s were typical for F. Typical F^- beam intensity versus Cs oven temperature data are displayed in Fig. 1.13. Of the sources tested to date for generating RIBs of F^- the direct extract EBPIS source offers, perhaps, the best prospect.

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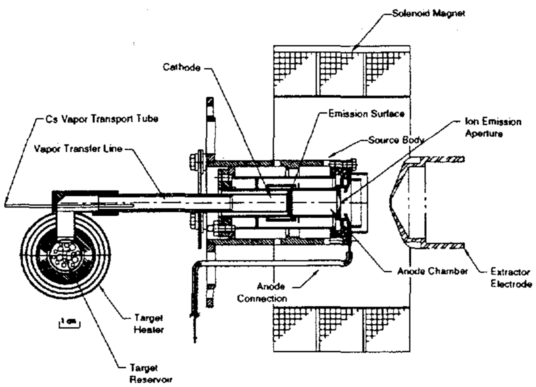

Fig. 1.12. Schematic drawing of the direct extract electron impact ionization source (EBPIS) for negative ion beam generation.

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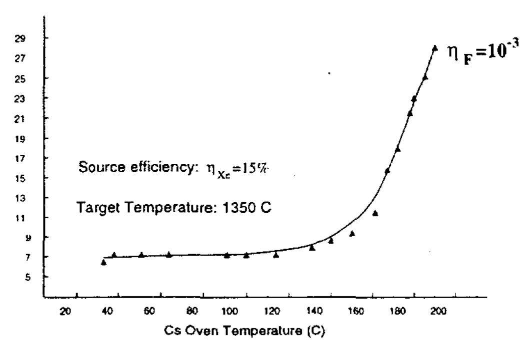

Fig. 1.13. F^- beam intensity versus Cs oven temperature extracted from the direct extracted negative ion source displayed in Fig. 1.12.

A NEGATIVE SURFACE IONIZATION SOURCE EQUIPPED WITH AN Ir/Eu SURFACE IONIZER

G. D. Alton, R. F. Welton,[1] B. Cui,[2] G. D. Mills, S. N. Murray

During this reporting period, a new concept negative surface ionization source was designed, fabricated and subjected to initial testing and evaluation for the generation of F^- ion beam at the target ion source test facility (TISTF-1). The source, illustrated schematically in Fig. 1.14, utilizes a low work function Ir/Eu surface ionizer which could theoretically have a work function as low as $\theta \cong 1.83$ eV.[3] (In actuality, we have not measured the work function but observe high electron drains at the operational temperatures of the ionizer (~1650°C) which suggest a low work function.) If the work function is low, the probability for ionizing highly electronegative atoms/molecules will, in principle, be quite high. For example, the group VIIA elements (F, Cl, Br, I and At) should ionize with unit probability. In addition, the essentially noble Ir metal surface should minimize the delay times because it reduces enthapies for adsorption between the atom/molecule and the ionizer surface which lead to poisoning effects in chemically active ionizers such as LaB_6. The ionizer is made by mixing Ir and Eu_2O_3 powders together in an Ir/Eu atomic percentage ratio of 75/25 followed by sintering the mix at ~ 1200°C. Semiempirical relations, developed for estimating the work function of a surface due to the adsorption of electropositive atoms/molecules, were used to estimate the minimum work function for the mix.[3] The ionizer and vapor transport tube are heated resistively to 1650°C, the critical temperature required to evaporate negative ions from the ionizer, by passing a current through the tubular structure. A fraction of the particles that pass through and strike the surface of the low work function cavity are ionized negatively as they evaporate from the surface. The optics of the source are identical to those used for the second generation EBPIS described previously in this report. To date, the source has been used to generate F^- beams by feeding low flow rates of SF_6 into the target chamber of the source. A typical mass spectrum taken during the measurement is shown in Fig. 1.15. As noted, rather large beams of O^- are also observed. Since the electron affinity of O is EA = 1.46 eV, this is evidence that the work function of the material is quite low, in keeping with the prediction. The source is presently being throughly characterized with emphasis on estimating the work function of the surface and measuring the ionization efficiencies of the source for F and Cl.

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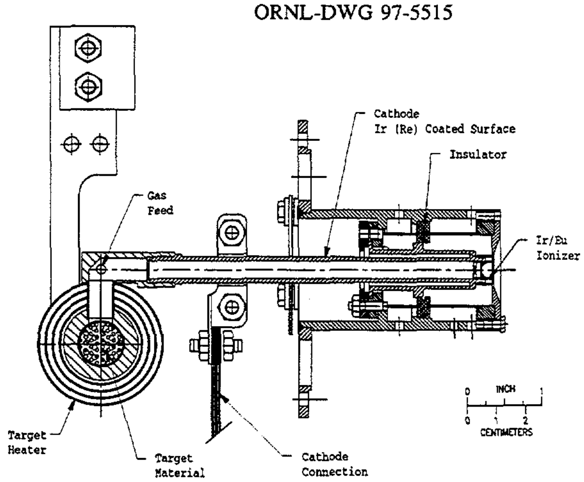

Fig. 1.14

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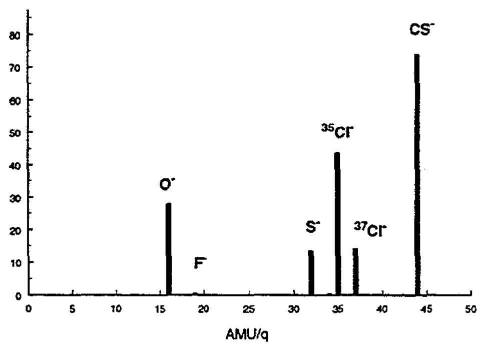

Fig. 1.15

1. ORNL postdoctoral associate/ORAU.

2. Joint Institute for Heavy Ion Research, Oak Ridge, TN, on assignment from China Institute of Atomic Energy, Beijing, China.

3. G. D. Alton, *Surf. Sci*, **175**, 226 (1986).

THE NEGATIVE SURFACE IONIZATION SOURCE EQUIPPED WITH A LaB_6 SURFACE IONIZER

G. D. Alton, R. F. Welton,[1] B. Cui,[2] G. D. Mills, S. N. Murray

A negative surface ionization source based on the use of a solid, spherical-geometry LaB_6 surface ionizer was also designed, fabricated and tested during this reporting period. The source is illustrated schematically in Fig. 1.16. During the test and evaluation period, the vapor transport tube and ionizer were operated at 1420°C. A variety of halogen-rich, gasesous, molecular compounds were fed into the source and effusive flow delay times and ionization efficiencies were measured for the halogens values. These materials (CF_4, CCl_4, CCl_2F_2 and SF_6) thermally dissociate to differing degrees at the operational temperature of the vapor transport tube and ionizer. The feed matrials were injected into the source at two points: through the target reservoir and directly sprayed onto the LaB_6 ionizer from the front side of the ionizer. The ionization efficiencies and effusive flow delay times are compared for each of the systems in Table 1.6.

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2. Joint Institute for Heavy Ion Research, Oak Ridge, TN, on assignment from China Institute of Atomic Energy, Beijing, China.

Table 1.6

	Bond Strength (eV)	Flow Rate (mol/s)	Efficiency (%)	Delay Time
$CF_4 \rightarrow F^-$	5.0	1.6×10^{14}	10^{-4}	5s
$CCl_4 \rightarrow Cl^-$	3.2	$9/7 \times 10^{13}$	0.34	400m
$CCl_2F_2 \rightarrow Cl^-$	3.2	2.1×10^{14}	1.04	140m
$CCl_2F_2 \rightarrow F^-$	5.2	2.1×10^{14}	10^{-6}	1s
$SF_6 \rightarrow F^-$	3.3	1.38×10^{14}	10^{-7}	30m

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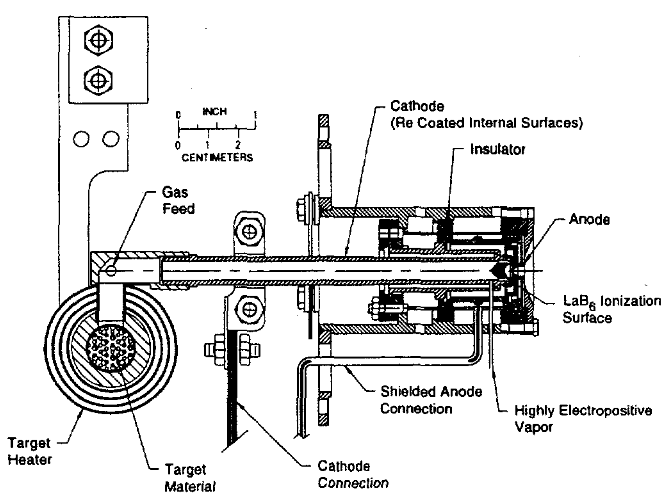

Fig. 1.16

THE DYNAMIC FLOW POSITIVE (NEGATIVE) SURFACE IONIZATION SOURCE

G. D. Alton, R. F. Welton,[1] B. Cui,[2] G. D. Mills, S. N. Murray

A versatile spherical-geometry positive (negative) surface ionization source has been designed, fabricated and initially tested. This new concept source can operate in either positive- or negative-ion modes without mechanical changes. A cross sectional representation of the source is shown in Fig. 1.17. The source is also simple and relatively inexpensive, which is important for RIB applications where contaminated sources must often be discarded. In addition, the source is designed so that parts can be easily changed and cleaned during routine maintenance. The source is equipped with a highly-permable Ir coated carbon-bonded-carbon-fiber (CBCF) composite ionizer, which has an intrinsic work function of ~ 5.29 eV. The spherical geometry ionizer (spherical radius: 2.5 mm; diameter: 6.25 mm) is machined from a CBCF matrix (fiber diameter: ~ 6 μm; density ~ 0.125 g/cm^3) and then coated with ~ 5 μm of Ir by use of chemical vapor deposition (CVD) techniques. Because of the high permeability of the CBCF structure, the species of interest can diffuse through the ionizer matrix with minimal delay. Since Ir has an intrinsically high work function, the source can be used directly for efficient generation of beams of the group IA elements and group IIA elements at lower efficiencies. For negative ion beam generation, Cs or another highly electropositive adsorbate must be dynamically fed through the Ir/C ionizer matrix to lower the surface work function. When operated in this mode, the source can be used to ionize highly electronegative atoms/molecules such as the group VIIA elements. In principle, the dynamic flow technique has the potential to overcome the chronic poisoning effects experienced with LaB_6 ionizers while enhancing the probability for negative-ion formation of atomic and molecular species with high to intermediate electron affinities. The operational parameters of the source were optimized for generation of both Cs^+ and F^-. For Cs^+ generation, the dependence of Cs^+ intensity on cesium oven temperature, ionizer temperture and extraction voltage were investigated; in negative-ion mode the dependence of F^- beam intensity on cesium oven temperature, ionizer temperature, extraction voltage and target temperature were studied. Figure 1.18 displays typical F^- beam intensity versus ionizer temperature. The results of these tests indicate that the source is reliable, stable, and easy to operate in either mode. Measured ionization efficiencies exceeded 60% for low intensity Cs^+ beams and were as high as 50% for F^-. No evidence of poisoning effects which plague more traditional negative surface ionization sources equipped with LaB_6 ionizers was found during operation in the negative ion mode.

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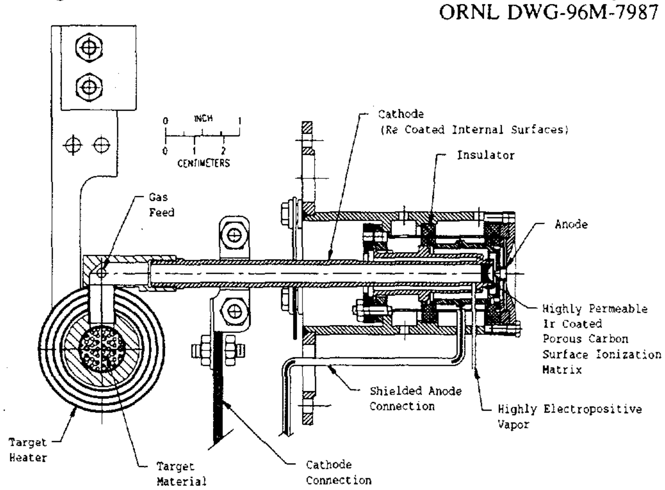

Fig. 1.17. Schematic drawing of the dynamic flow positive(negative) surface ionization source.

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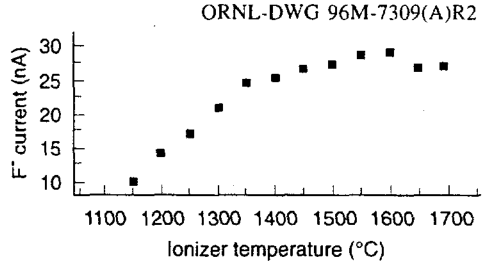

Fig. 1.18. F^- beam intensity versus ionizer temperature. Cs oven temperature: 200°C; Extraction voltage: –300 V. Feed material: AlF_3. Target temperature: 500°C.

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THE KINETIC EJECTION NEGATIVE SURFACE IONIZATION SOURCE

G. D. Alton, R. F. Welton,[1] B. Cui,[2] G. D. Mills, S. N. Murray

A first of its kind, negative surface ionization source type which utilizes a Cs^+ ion beam to kinetically eject highly electronegative atoms/molecules from a LaB_6 surface ionizer was conceived, fabricated and awaits testing. The source, shown schematically in Fig. 1.19, was conceived to both overcome poisoning effects incumbent with sources equipped with conventional thermal evaporation-type LaB_6 surface ionizers and as a means of dissociating molecules which are transported from the target material to the ionizer surface in molecular form. To effect both processes, a Cs^+ ion beam, generated by positive surface ionization as it passes through a highly permeable, flat-surface Ir/C surface ionizer, is accelerated against the negatively biased LaB_6 surface ionizer. The energetic Cs^+ particles kinetically dissociate molecular constituents and eject electronegative atoms/ions from the surface of the ionizer resulting in desorption of the species of interest. The negative ion beam is extracted from the aperture of the LaB_6 ionizer. Since the work function for LaB_6 is reasonably low ($\phi = \sim 2.7$ eV), the probability for forming negative ions from members of the group VIIA elements (F, Cl, Br, I and At) should, in principle, be very high (unity). The source awaits test and evaluation at the TISF-1. Another version of the source is being designed which will feature improved geometry for trapping atoms/molecules on a cylindrical LaB_6 cathode surface. Again the atoms/molecules are kinetically ejected from the LaB_6 surface by Cs^+ particle bombardment of the LaB_6 surface. If significant improvements in the ion formation efficiencies can be realized with this concept, an on-line version of the source will be fabricated for use in generating F^- and Cl^- RIBs for the HRIBF research program.

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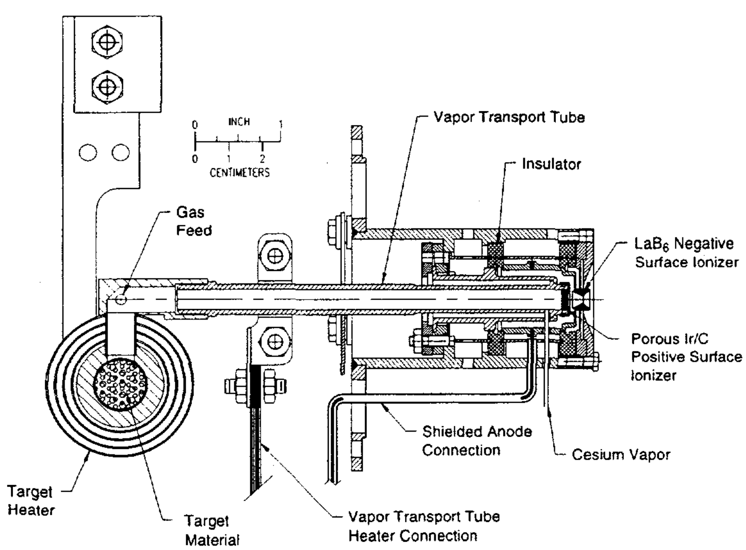

Fig. 1.19

AN EFFUSIVE FLOW DELAY TIME MEASUREMENT SYSTEM

R. F. Welton,[1] G. D. Alton, B. Cui,[2] G. D. Mills, S. N. Murray

The principal delay times associated with the RIB generation process are the time required for diffusion through and release from the target material, and the time required for effusive-flow of the species into the ionization chamber of the source. If these times are long with respect to the lifetime of the species of interest, then the beam intensity will be seriously compromised. Off-line measurement techniques have been developed during this reporting period which permit accurate determination of the ionization efficiencies and effusive-flow delay-times of a variety of solid or gaseous feed materials containing the stable complement of the RIB species of interest in an arbitrary ISOL ion source. These techniques are viewed as important tools for exploring these limiting aspects of the RIB generation process. Four separate systems have been designed, developed and used in measuring the effusive flow delay time for specific materials in both the EBPIS and surface ionization sources that permit the introduction of extremely small, well defined flow-rates of gaseous feed materials containing the element of interest. The flow-rate systems include: a measurement and control system for introducing mass flow rates as low as 10^{10} particles/s; a high temperature valve system with well defined opening and closing characteristics which can operate at temperatures up to 2000°C for introducing strongly bound molecular gases containing chemically active elements of interest and high volatility solid feed materials; a low temperature injection nozzle for introducing molecular feed materials, containing the chemically active elements of interest, which are easily thermally dissociated into the source; and a system that can be used to insert well defined amounts of solid materials into the source. The hot valve and low temperature nozzle systems are schematically illustrated in Fig. 1.20. A typical effusive-flow delay time measurement for F in the EBPIS, using SF_6 as the feed material, is shown in Fig. 1.21.

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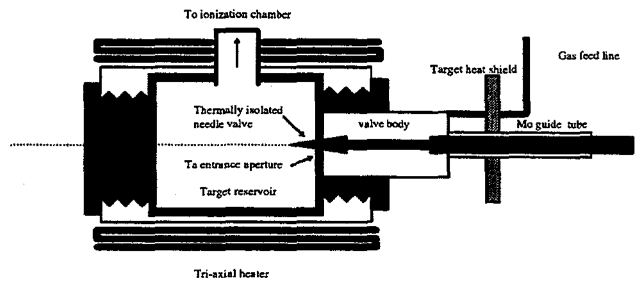

Fig. 1.20

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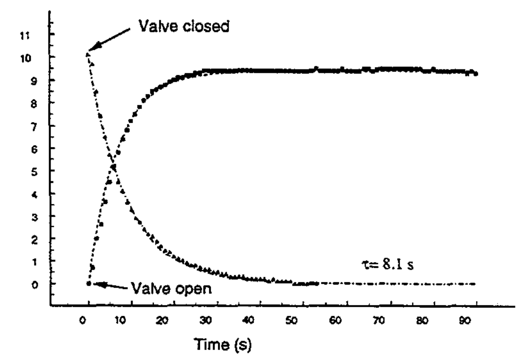

Fig. 1.21

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ADVANCED ECR ION SOURCE CONCEPTS

G. D. Alton, F. W. Meyer, J. R. Beene

Despite the steady advance in the technology of the ECR ion source, the present state-of-the-art has not yet reached full potential in terms of charge state and intensity within a particular charge state, in part, because of the narrow band width, single-frequency microwave radiation used to heat the plasma electrons. We have proposed new fundamentally important methods for enhancing the performance of ECR ion sources through the use of: (1) an ECR ion source with a uniformly distributed central magnetic field region between mirror fields in combination with single-frequency microwave radiation to create a large uniformly distributed ECR "volume" (spatial domain)[1-3] or (2) the use of broadband frequency domain techniques (variable-frequency, broad-band frequency, or multiple-discrete-frequency microwave radiation), derived from standard TWT technology, to transform the resonant plasma "surfaces" of traditional ECR ion sources into resonant plasma "volumes."[3,4] These sources are illustrated, schematically in Fig. 1.22 (spatial domain) and Fig. 1.23 (frequency). Creating a large ECR volume will result in significantly greater interaction of the microwave radiation with the plasma electrons, both in terms of total power absorptivity and in a more uniform spatial distribution of the absorptivity. The creation of a large ECR plasma "volume" permits coupling of more power into the plasma, resulting in the heating of a much larger electron population to higher energies, thereby producing higher charge state ions and much higher intensities within a particular charge state than possible in present forms of the source. During this reporting period, funds were awarded for design and evaluation of a compact, permanent magnet ECR ion source that can be configured in each of the two geometries for test and evaluation. A first phase STTR grant was awarded to Lambda Technologies, Raleigh, NC, for evaluating each of the frequency domain scenarios using the ECR3 ion source, located in the ECR based Atomic Collision Physics Group of the Physics Division. We have procured computer codes for designing the magnetic field and ion optics codes for simulation of ion extraction from each of the source scenarios. We have procured magnetic field measuring equipment and begun fabrication of a test facility for evaluation of the permanent magnet source and we have begun collaborative experiments with personnel from Lambda Technologies designed to evaluate each of the frequency domain scenarios. These ECR ion source concepts offer exciting opportunities to significantly advance the state-of-the-art of ECR technology and, as a consequence, open new opportunities in fundamental and applied research and for a variety of industrial applications. If successful, these ECR ion source concepts will significantly impact accelerator based research programs by providing higher energy ion beams for an extended number of heavy-ion species with adequate intensities for heavy-ion atomic and nuclear physics research, as well as for a variety of applied research and commercial applications.

ORNL-DWG 95M-10248R4

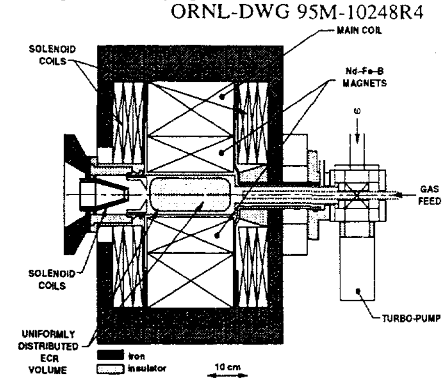

Fig. 1.22

ORNL-DWG 95M-10049

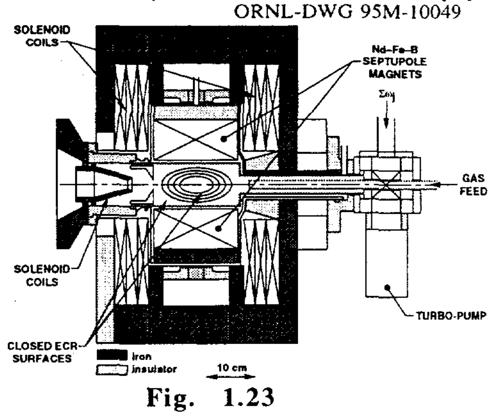

Fig. 1.23

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1. G. D. Alton and D. N. Smithe, *Rev. Sci. Instrum.* **46** 1 (1994).
2. Microwave Electron Cyclotron Resonance (ECR) Ion Source with a large, uniformly distributed axially symmetric, ECR plasma volume, US Patent, No. 5,506,475.
3. G. D. Alton, *Proceedings of the International Conference on Cyclotrons and their Applications*, ed. J. C. Connell, World Scientific, 1996, pp. 362 - 371.
4. Patent applied for (ESID 1699-X).

RF ION SOURCE DEVELOPMENTS

R. Lohwasser,[1] *G. D. Alton, R. F. Welton*[2]

The goal of this project is to develop low-density, plasma-sputter negative ion sources as well as high-efficiency, high-density positive ion sources, based on rf-plasma excitation, for potential use at the HRIBF. An rf-plasma diagnostic test stand was constructed for use in designing and optimizing rf antennae, rf matching network systems and Langmuir probes; for determining rf power/plasma coupling efficiencies, antenna radiation patterns and polarization directions; and for measuring the fundamental properties of rf generated plasmas including plasma density, electron temperature, electron energy distributions and the degree of ionization. The test stand, schematically illustrated in Fig. 1.24, consists of a vacuum chamber, a turbomolecular vacuum/roughing pump system and control unit, pressure monitoring gauges, an electromagnet for radial confinement of the plasma, a 80 MHz rf power supply, a 50-ohm rf feedthrough, an rf antenna, a Langmuir probe for measuring the plasma parameters and a glass tube in which plasma columns are created. The test stand enables the rapid interchange of prototype rf antennas and Langmuir probes for their respective evaluation in igniting and measuring fundamental properties of plasmas. Langmuir probes are used to determine properties of plasmas including electron density, electron temperature, plasma potential and degree of ionization. These parameters can be derived from the electron/ion signals measured with the probe submerged in the plasma. The major thrust of the work, up until the present time, has been directed toward designing, developing and evaluating, high-Q rf antennae that will efficiently couple rf power into the plasma. Thus far, we have designed and evaluated five different rf antenna designs. Each antenna is evaluated on the basis of the power required to ignite the plasma, the minimum pressure required for ignition and the properties of the plasmas they produce. Antennae have been developed which can maintain a plasma discharge at a power level as low as 1 W. Stable operation can be achieved at power levels as low as 5 W. In developing the antennae, a technique was discovered which greatly reduces the time required to reach an optimum design. The technique is to vary the coil spacing so that the coil, in combination with the rf feedthrough are resonant at the operating frequency of the rf power supply (in our case, 80 MHz). The highest plasma densities achieved so far were for a 4 turn, self resonant helical antenna (30.5 mm OD), at a magnet field strength of 560 Gauss, a rf power of 200 W and an Ar pressure of 1.8 m Torr. Under these conditions, the electron density reaches values of ~10^{13} cm^{-3}, corresponding to an ionization efficiency of ~10%. Electron density versus rf power for three different antennae are displayed in Fig. 1.25. In the near future, we will apply the same principles and techniques in the optimum design of a small diameter antenna for potential use in generating positive ion beams for on-line HRIBF operation.

ORNL-DWG. 97-5516

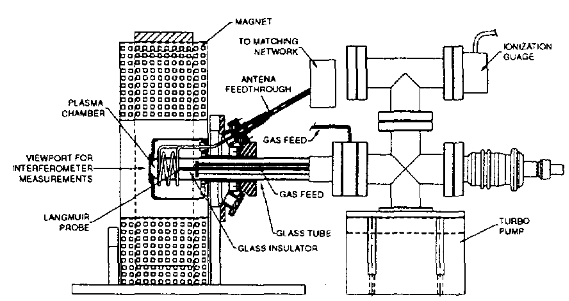


Fig. 1.24

ORNL-DWG 97-5517

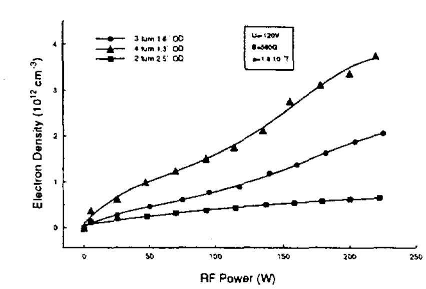


Fig. 1.25

1. Ludwig Maximilians University, Germany.
2. ORNL postdoctoral associate/ORAU.

A COMPACT RF PLASMA DISCHARGE SOURCE

R. F. Welton,[1] D. Becher,[2] G. D. Alton, G. D. Mills, J. Dellwo,[3] S. N. Murray

A versatile rf powered multi-cusp-field source that can be operated in either positive or negative modes was conceived, fabricated, and evaluated during this reporting period. The source, schematically illustrated in Fig. 1.26, was conceived for potential use for both accelerator (injector) ion source applications where high intensity is desired and ISOL (radioactive beam) applications where molecular dissociation and ionization efficiency of trace material is important. The source is equipped with an insertable/removable filament for adding supplemental electrons to the discharge. Under optimal conditions, the ionization efficiency of a trace flow of Xe was found to range between 8% and 16% with a ~200% increase in ionization efficiency realized with the addition of supplemental electrons. This work quantifies the performance enhancement that can be expected with the addition of a relatively simple filament structure to an inductively coupled rf ion source operating at modest powers. The source offers the prospect of being an effective means for dissociating molecules. For example, the source can be used to dissociate and ionize members of the traditionally difficult gaseous molecular species such as N_2, CO, CO_2, NO and NO_2, etc., with measured dissociation fractions of N^+/N^+_2 for N_2 feed gas ranging up to 60%. Total analyzed beam intensities, ionization efficiencies, molecular dissociation fractions and emittances were measured for a number of species with the filament on and off as functions of operating pressure, rf power and extraction voltage. Preliminary measurements suggest that the emittances of ion beams from the source are quite low. The use of the filament resulted in a lowering of the normalized emittance from 2.4 to 2.12 π mm mrad $MeV^{1/2}$ for the 90% contour of the beam. In addition, the minimum pressure for stable plasma operation was reduced on the average by a factor of four. The electrons appear to benefit the source plasma in three important respects: (1) the minimum operating pressure is lowered four fold (to 4×10^{-4} torr in the source), (2) the emittance is improved, and (3) the electron density is increased which subsequently lowers the plasma potential.

1. ORNL postdoctoral associate/ORAU.
2. Science and Engineering Semester Program participant, University of Nebraska.
3. Partial support from the Joint Institute for Heavy Ion Research.

ORNL-DWG 97-5506

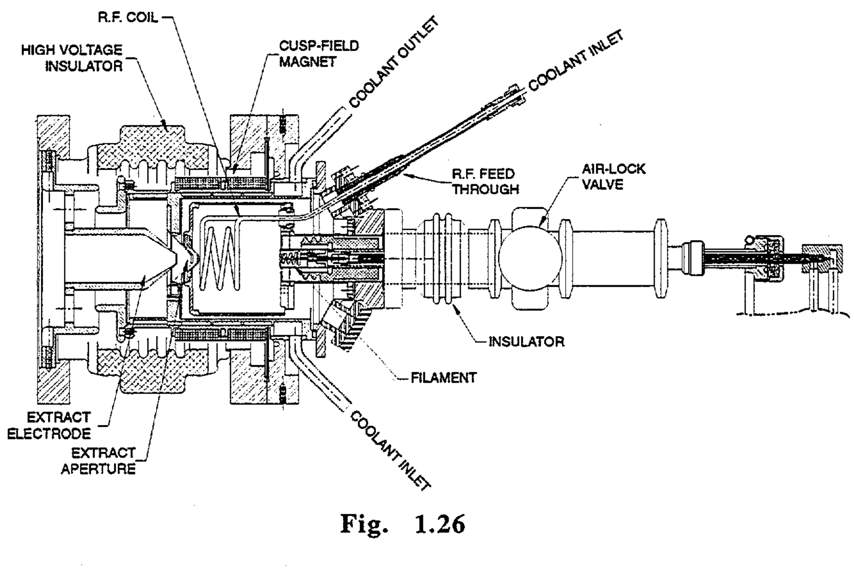


Fig. 1.26

A MULTI-SAMPLE CESIUM-SPUTTER NEGATIVE ION SOURCE FOR RIB APPLICATIONS

G. D. Alton, G. D. Mills, C. A. Reed[1]

A multiple sample source based on the conical geometry surface ionizer, described in the previous Physics Division Progress Report was designed and is nearing completion for potential use for generating RIBs of long-lived species in batch mode and for stable generation of beams for UNISOR ion implantation studies. The source, illustrated schematically in Fig. 1.27, is equipped with a conical geometry cesium surface ionizer which is positioned in close proximity to a negatively biased sample containing the element from which negative ion beams are to be generated. The electrode system is designed so that the cesium ion beam at impact, bombards a large area of the sample surface. This is consistent with the good cesium ion beam/sputter sample surface overlap requirements necessary for the efficient generation of RIBs by this technique. The Cs beam impacts the surface and sputters the material of interest, a fraction of which is negatively ionized. For batch-mode RIB generation, the Cs^+ beam at impact with the sputter sample containing the radioactive species must be equal in size or slightly larger than the primary beam size used to activate the sample. The Cs^+ ion beam current density distribution as it impacts the sample surface is approximately uniform with the exception of the sharp peak in the center of the sample and is sufficiently large to overlap a 6 mm diameter primary ion beam. For RIB applications, the radioactive material may be transported from the target to the negatively biased, condensation surface from which the material is sputtered, through a hot vapor transport tube so that the RIB can be generated in CW mode. Alternatively, the radioactive species may be formed within the sample by nuclear reactions by irradiation of the sample with high energy protons, deuterons, ^3He or ^4He projectiles and subsequently sputtered from the sample in batch mode. The latter technique is appropriate whenever the lifetime of the radioactive species exceeds several tens of minutes. The source will serve as a prototype for possible use in RIB applications and as an alternative to the plasma-sputter negative ion source. The source is presently being considered for batch processing RIB generation with long-lived elements with large electron affinities, such as $^7BeO^-$, $^{18}F^-$, ^{34}Cl, ^{56}Ni, $^{72,73,74,76}As$, $^{74,76,78}Br$, and $^{70,71,72}Se$. A simplified version of this source will be used to generate beams of ^{56}Ni for the HRIBF research program.

1. UNISOR, Oak Ridge Institute for Science and Education, Oak Ridge, TN.

ORNL-DWG 97-5507

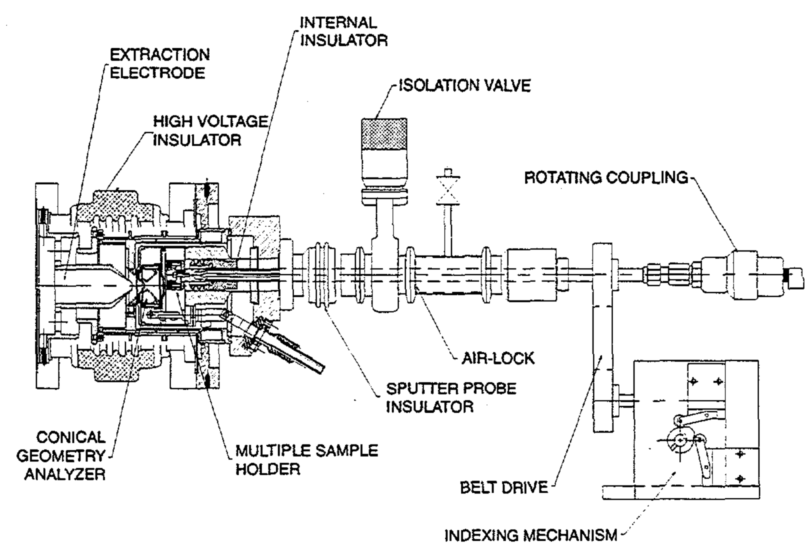


Fig. 1.27

A SECOND TARGET/ION SOURCE TEST FACILITY

G.D. Alton, G. D. Mills, C. A. Reed[1]

During this reporting period, a second Target/Ion Source Test Facility (TISTF-2), located in the basement of Building 6000, was designed and construction initiated. The facility will be used in parallel with the initial test facility (TISTF-1) to test and evaluate new concept targets and ion sources and to measure the delay times attributable to diffusive and effusive flow from targets to the ionization chamber of RIB sources. Figure 1.28 schematically displays a side view showing the layout of the facility. The TISTF-2 consists of a target/ion source, a beam transport lens, a magnet for mass selection, Faraday cups for monitoring the beam prior to and following magnetic analysis and ancillary equipment (power supplies, vacuum pumps, electrometers, etc.) necessary for operation of the facility. The mass analysis system ($\rho = 0.61$ m; $\theta = 45^{\circ}$ degree; entrance angle: 0°; exit angle: 11°) is predicated on the use of an existing magnet, modified to provide mass analysis for 100 keV ion beams of H through U. The optics of the beam transport system were designed by use of GIOS.[2] During this reporting period, the TISTF-2 was enclosed with fencing with keyed-entry, sliding-doors, the magnet was equipped with specially designed pole pieces and vacuum chamber, and the beam transport einzel lens was designed and fabricated. The magnetic analysis system is presently being assembled. During the present fiscal year, the facility will be equipped with a RIB ion source interface, electrical bussing, a high voltage platform and a 15 kW motor generator set for powering ion sources and ancillary equipment mounted on the high voltage platform.

1. UNISOR, Oak Ridge Institute for Science and Engineering, Oak Ridge, TN.
2. GIOSP is a beam transport code developed at the University of Giessen, Giessen, Germany, by Professor Hermann Wollnik and colleagues.

ORNL-DWG 97-5518

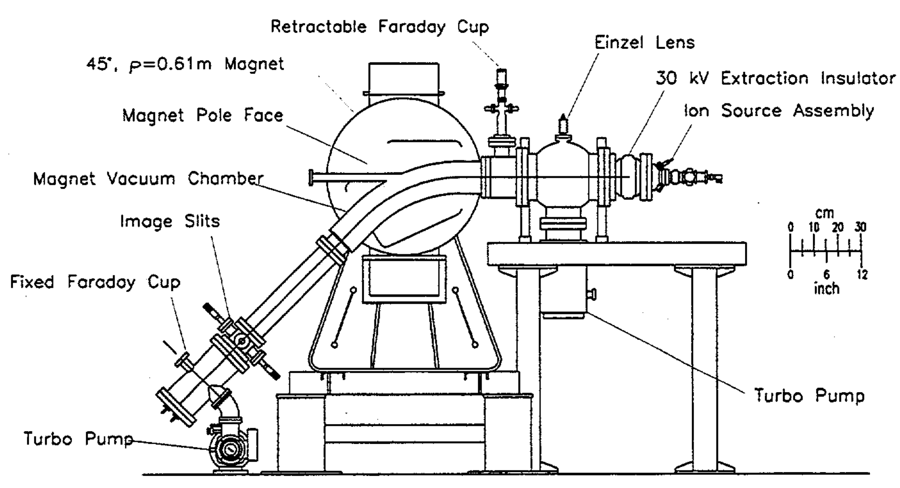


Fig. 1.28. Side-view of the second Target Ion Source Test Facility (TISTF-2) under construction in the basement of Building 6000 for developing new ion source concepts for potential RIB generation.

ENERGY ANALYSIS SYSTEM

G. D. Alton, B. Cui,[1] G. D. Mills

An apparatus for determining the intrinsic energy spreads in ion beams extracted from RIB sources and induced in the beam by sequential charge exchange in the negative ion formation process has been conceived, designed and fabrication was initiated during this reporting period. The energy analysis system consists of an electrostatic deflection system followed by a parallel plate energy analyzer with an energy resolution of 0.5%. In order to determine the energy spread with the required accuracy (1.25 to 2.5 eV), it will be necessary to retard the beam energy to low values (~ 250-500 eV) prior to energy analysis; this will be accomplished by passing the beam across a single gap electrode system located between the entrance plane and the entrance to the energy analyzer. The device is housed in a 0.61 m diameter scattering chamber located immediately following the charge exchange cell on the TISTF-1 as displayed in Fig. 1.29. Energy spectra will be derived by digitally varying the voltage with a 20 bit DAC mounted at high voltage and controlled with a fiber-optic coupled power supply located at ground potential. A commercially available multichannel scaling analysis software package will be used to control the voltage and acquire the data. This system will be implemented during next fiscal year. High on the priority list for study are measurements of the energy spread induced by collisional processes during charge exchange and the intrinsic energy spreads associated with the sputter negative-ion formation process. Both measurements are fundamentally important for RIB applications and for understanding the mechanisms involved in the negative-ion formation process by sputtering from low work function surfaces.

1. Joint Institute for Heavy Ion Research, Oak Ridge, TN, on assignment from the China Institute of Atomic Energy, Beijing, China.

ORNL-DWG 97-5508

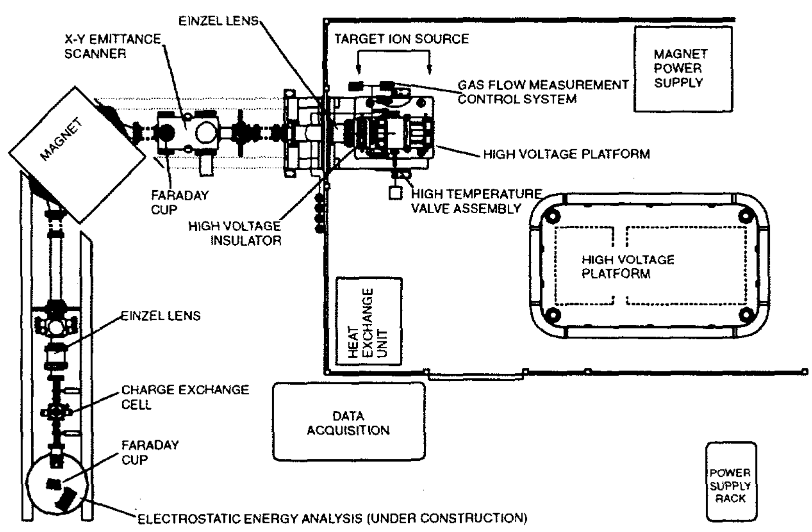


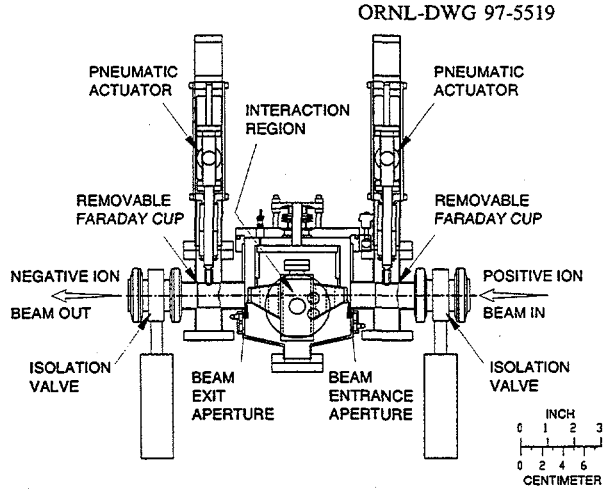
Fig. 1.29. A schematic representation of the TISTF-1 equipped with the energy analysis system.

THE Li, Na OR Mg CHARGE EXCHANGE CELL PROJECT

G. D. Alton and D. L. Haynes

During collisions between an ion, neutral atom, or molecule, and another ion, atom or molecule, an electron can be transferred from one of the colliding partners to the other with high probability, depending on the collision energy and the ionization potentials and/or the electron affinities of the colliding partners. This process is referred to as charge exchange and is a very efficient means of converting positive ion beams into negative ion beams. In the previous Physics Division Report,[1] a Cs charge exchange cell was described which has subsequently been implemented for routine use at the HRIBF for converting initially positive ion beams into negative ion beams for injection into the 25 MV tandem. The cell has proved to be extremely reliable and easy to operate. However, as a consequence of the interaction between the colliding partners, momentum is also transferred. In general, the momemtum transfer process takes place at relatively large impact parameters for which the projectile scattering is small and the product ion is scattered nearly perpendicular to the impact direction. However, from the standpoint of beam quality degradation, low momentum transfer interactions are desirable. Heavy donor materials, such as Cs, scatter more than light donor materials such as Li. The charge exchange process is characterized as being either symmetrical (resonance) or asymmetrical (nonresonant). For the symmetrical situation, collisions take place between identical species for which the energy defect, ΔE, is zero. In certain cases, ΔE can be close to zero for dissimiliar colliding partners. This case is referred to as an accidental resonance. This situation can be problematical because the cross sections for charge transfer are maximum at zero relative velocity. This has proved to be a problem when Cs is used to convert positive halogen beams to negative ion beams because of the small energy defect. In order to avoid the accidental resonance for the halogens and reduce scattering effects which occur when Cs is used, we are designing a charge exchange cell which can be used with Li, Mg or Ca exchange vapors. A horizontal cross-sectional view of the cell is displayed schematically in Fig. 1.30. The cell fits into the same housing as the original cesium charge exchange cell and is designed to recirculate the charge exchange vapor and thereby extend the lifetime of the cell. The cell uses heaters clamped against the body of the stainless steel cell for heating elemental charge exchange material to the temperature which optimizes the vapor density in the path of the beam. A temperature of ~ 450°C produces a nearly optimum target thickness (~ $2 \times 10^{15}/cm^2$). During this reporting period, engineering drawings for construction of the cell were initiated. During the present fiscal year, the cell will be fabricated and evaluated on TISF I; following characterization, the cell will be made available for routine RIB applications.

ORNL-DWG 97-5519



HRIBF RECIRCULATING Mg CHARGE EXCHANGE CELL

Fig. 1.30

1. "The Charge Exchange Cell Project," G. D. Alton, J. Dellwo, D. L. Haynes, and S. N. Murray, *Physics Division Progress Report for Periond Ending September 30, 1994, ORNL-6842*, p. 1-31.

MODIFICATIONS TO THE RIB TARGET/ION SOURCE ASSEMBLY

G. D. Alton, C. A. Reed,[1] C. Williams[2]

The design philosophy for handling radioactively contaminated sources is much the same as that utilized at the CERN-ISOLDE which relies on the ability to remotely remove and install the modular vacuum housing which contains the TIS assembly robotically. The operational lifetime of a typical CERN-ISOLDE TIS is limited by target lifetimes and radiation damage to elastomer gaskets. The CERN-ISOLDE source has many elastomer gaskets which are subject to this failure mode. We have made a concerted effort to eliminate as many failure modes as possible in the ORNL TIS design. In the ORNL TIS design, almost all elastomer gaskets have been eliminated from the modular vacuum housing assembly, either by use of knife-edge metal-to-metal gaskets or metal "O-ring" seals, in order to minimize potential catastrophic vacuum failure due to radiation damage to elastomer gasket materials. The HRIBF target/ion source assembly is illustrated schematically in Fig. 1.31. As noted, the integrated ion source assembly consists of the high temperature target/ion source, a modular vacuum housing, an interface flange, solenoidal magnets, pneumatic shutters, a positionable extraction electrode system, and high voltage insulators. During this reporting period, the original source design was carefully scrutinized with the objective of eliminating stack-up errors between assemblies to reduce misalignment problems whenever the source assemblies and source modules are interchanged. The extraction electrode drive mechanism has been redesigned to eliminate squirm and the screw-on extractor nozzle has been replaced with a bayonet type attachment mechanism to facilitate fast removal during cleaning of the nozzle. In addition, the pneumatic pistons used to engage/disengage the modular vacuum housing from the mating stationary assembly, are ordinarily sealed with elastomer gaskets which relatively often fail due to radiation damage. We have redesigned the pneumatic piston to accommodate flexible layered carbon gaskets which have been thoroughly tested for many hours of continuous operation without leakage or any evidence of any mechanical failure mode. This design required essentially no further development time. Carbon is not sensitive to radiation damage and the new design, therefore, should eliminate the possibility of failure due to radiation damage effects. The source has also been equipped with x-y steerers to enable efficient beam transport into the first stage mass separation system. The steerer plate assembly is modular and designed to fit into the existing ion source housing without any additional modifications to the assembly, as noted in Fig. 1.31.

1. UNISOR, Oak Ridge Institute for Science and Engineering, Oak Ridge, TN.
2. Consultant, Gilbert/Commonwealth Engineering Consultants, Oak Ridge, TN.

ORNL-DWG 97-5522

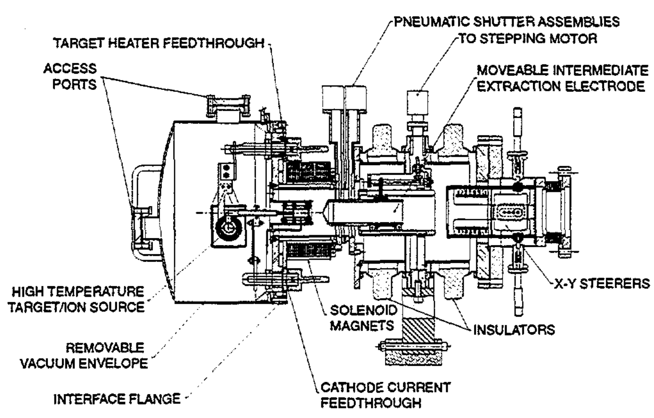


Fig. 1.31

THERMODYNAMIC EQUILIBRIUM COMPUTATIONS

G. D. Alton, R. Jarvis,[1] R. F. Welton[2]

During this reporting period, three thermodynamic data base computer codes were acquired which greatly facilitate our capability to compute critically important information for operating RIB targets and ion sources as well as to enhance our understanding of the fundamental processes which limit intensities of short-lived RIB species. These codes include ThermoCalc,[3] DICTRA,[4] and HSC[5] thermodynamic data base codes, as well as the diffusion code SCIENTIST[6]. These codes have been used to calculate adsorption/desorption isotherms of various RIB species on solid surfaces, thermal dissociation fractions of molecules, chemical reaction rates, diffusion release of species from metallic and non-metallic target materials and the vapor pressures of more than 25 metals and candidate target materials. The latter information is critically important for operating the TIS since the temperature of the target cannot be raised above a critical value set by the vapor pressure above which the ionization efficiency of the source is compromised ($\sim 2 \times 10^{-4}$ Torr). A general technique for calculating molecular heats of adsorption derived from atomic adsorption data has also been utilized. The ability to predict thermal dissociation fractions and chemical reaction rates provides valuable information about the molecular form of the desorbed species and the species which finally exit the source. In addition to the commercially available codes, we have continued our efforts to develop in-house codes for studying the effusive flow process. The geometrical effects of the ion source enclosure on effusive transport are modeled using the Monte Carlo simulation technique.

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1. SURA/University of Connecticut, Storrs.
2. ORNL postdoctoral associate/ORAU.
3. Thermo-Calc is a thermodynamic equilibrium computer program developed by the Royal Institute of Technology, Stockholm, Sweden.
4. DICTRA is a multi-component diffusion computer program developed by the Royal Institute of Technology, Stockholm, Sweden.
5. HSC is a commercially available thermodynamic equilibrium computer code marketed by Outokumpu Research Py, Peri, Finland.
6. SCIENTIST is a commercially available computer code marketed by Micromath Scientific Software, Salt Lake City, UT.

ON-LINE RESULTS FOR ARSENIC AND FLOURINE RADIOACTIVE ION BEAMS FROM HRIBF TARGET/ION SOURCES

D. W. Stracener,[1] H. K. Carter,[2] J. Kormicki,[2,3] A. H. Poland, J. B. Breitenbach,[2] C. A. Reed,[2] G. D. Mills, J. C. Blackmon,[4] M. S. Smith, D. W. Bardayan[5]

The on-line testing and development of a modified version of the target/ion source[6] for the HRIBF facility was carried out at the UNISOR on-line isotope separator. The following modifications were made specifically for a liquid germanium target which will be used to produce radioactive arsenic ion beams. Since the vapor pressure of germanium is 10^{-4} Torr at 1100°C, it was expected that this would be the maximum operating temperature for the target. With this in mind, the target heater was simplified to a single-pass design, with an attached heat shield. The cathode current connection was moved from midway along the cathode transfer tube to the rear-most point, to ensure that the entire transfer line will be at the highest possible temperature. A carbon target holder, with a 1-mm-thick entrance window, is used since tantalum reacts strongly with germanium. The germanium target, designed to stop 40-MeV protons, is 4 mm thick by 9 mm in diameter.

Several copies of the target/ion source were constructed and tested off-line to determine typical operating parameters. The single-pass target heater has operated reliably over a wide range of target temperatures, from 900°C, with no heater current applied, up to 1570°C with a heater current of 480 A. Moving the cathode connection to the rear of the transfer tube enables the entire transfer line to be operated at temperatures in excess of 1700° C with a current of approximately 350 A. This temperature was measured at the coldest point, next to the cathode current connection. Typical ion source efficiency for Xe is 10% - 15% with the cathode current of 350 A and anode current of 150 mA at 150 volts. For on-line experiments, the Xe gas inlet is restricted to 0.3 mm to reduce the flow of reaction products into the gas line. With this arrangement, the apparent Xe efficiency is reduced to 3%.

The performance of the target/ion source for the production of arsenic beams was tested using the (p,n) and (p,2n) reactions on a natural 99.999% pure germanium target. On-line data clearly show an improvement in yield as the target temperature is increased. Using these measured arsenic yields, we show that the target can be operated at temperatures up to 1300°C with no loss of Xe efficiency. However, a significant hold-up time in the target/ion source was also observed. Using measured yield curves and calculated production rates,[7] the calculated efficiency of the ion source at 1300°C was 0.8 ± 0.3% for ^{70}As and 0.5 ± 0.2% for ^{69}As. The ^{72}As ($t_{1/2}$ = 26.0 h) activity was used to measure the target/ion source hold-up time, which was 3.6 ± 0.3 hours at 1270°C.

The performance of a similar ion source for the production of ^{17,18}F isotopes was also investigated. The only changes in the target/ion source from that described above are the target holder and target material. The target material is 3-μm-thick Al_2O_3 fibers bound with SiO_2 (2% by weight) and the target holder is made of tantalum and welded to the transfer tube. The reactions used were ^{16}O(d,n)^{17}F ($t_{1/2}$ = 64.5 s) and ^{18}O(p,n)^{18}F ($t_{1/2}$ = 110 m). Approximately 88% of the observed radioactive fluorine was found in mass 44 (45) corresponding to Al^{17}F (Al^{18}F), with small amounts found at other masses which could correspond to the following molecules (% yield): F(3), HF(2) and SiF(7). In addition, the following masses (molecules) were checked and negligible amounts of radioactive fluorine were observed: 28(BeF), 42(NaF), 47(BeF_2), 58(KF), and 62(AlOF). At a target temperature of 1470° C, the efficiency of this source for Al^{17}F was 0.0052 ± 0.0008%, and the efficiency for Al^{18}F was 0.06 ± 0.02%. The hold-up time for Al^{18}F was measured at 1470°C and found to be 16.4 ± 0.8 minutes.

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1. University of Tennessee, Knoxville, and Joint Institute for Heavy Ion Research, Oak Ridge, TN.
2. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
3. Vanderbilt University, Nashville, TN.
4. University of North Carolina at Chapel Hill, Chapel Hill.
5. A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, CT.
6. G. D. Alton et al., *Physics Division Progress Report, ORNL-6842, September 30, 1994.*
7. J. Gomez del Campo (private communication), using a statistical model code, LILITA.

A PROTOTYPE COMPOSITE TARGET/HEAT-SINK SYSTEM

C. Williams[1] *and G. D. Alton*

A prototype composite target/heat-sink system now being designed at the HRIBF is displayed in Fig. 1.32. The device can be inserted into or removed from the target/ion source through a vacuum interlock port. The target/heat sink system consists of a highly permeable matrix material such as reticulated-vitreous-carbon fiber (RVCF), onto which is plated the target material of interest. The matrix is bonded to a C-beam stop of sufficient length to stop the energetic primary beam; the composite matrix/C-beam stop assembly is screw attached to a Cu/H_2O heat-sink. The primary beam, which produces the radioactive species, enters the matrix after passing through a thin Ir coated C window. The beam is slowed down in the composite target matrix where it deposits energy and finally comes to rest in the C beam-stop. The energy deposited in the composite matrix will raise it to a maximum, steady-state temperature, depending on the physical, chemical and thermodynamic properties of the materials which make up the assembly and those of the heat exchange medium used to remove heat through conduction at the beam-stop/heat-exchange interface. The energy loss (stopping power) function is calculated by the use of the computer code SRIM.[2] This data is used as input into the finite element computer code, ANSYS[3] which is used to determine the heat transport from the target matrix to the heat-sink. The FEA code FLOTRAN[4] is used to determine the heat transfer coefficient between the H_2O and Cu interface. As a matter of policy, the target thickness where the particle energy loss becomes very large is always chosen so that high energy density region of the dE/dx curve occurs in the beam stop to avoid excessive heating of the target material itself. This region corresponds to the Bragg peak where the projectile energy is below the Coulomb barrier and, therefore, is ineffectual for producing nuclear reactions.

1. Consultant, Gilbert/Commonwealth Engineering Consultants, Oak Ridge, TN.
2. SRIM - The Stopping and Range of Ion in Matter, J. F. Ziegler, IBM Research, Yorktown Heights, New York.
3. ANSYS is a finite element computer code designed to solve thermal transport, as well as other problems; the code is a product of Swanson Analysis Systems, Inc., Houston, PA.
4. FLOTRAN is a finite element code for calculating heat transfer coefficients between media interfaces; the code is a product of Swanson Analysis Systems, Inc., Houston, PA.

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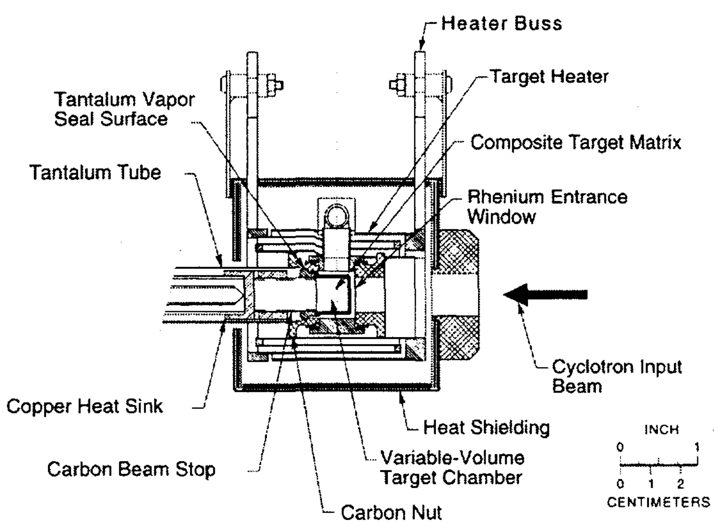

Fig. 1.32. A prototype composite target/heat-sink system for use in generating RIBs at the HRIBF.

MEASUREMENT OF PRODUCTION RATES AND INDUCED RADIOACTIVITY IN PROTON/DEUTERON REACTIONS ON THICK TARGETS

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As a part of the development of the HRIBF, a series of experiments was carried out to measure the thick target yields of proton and deuteron reactions on elements. In addition, the residual radioactivity generated was measured in order to provide estimates for handling the radioactivity. The results of these experiments will be used to select possible radioactive beams and to estimate their intensities.

Proton and deuteron beams of varying energies from the 25-MV tandem accelerator were used to bombard various thick targets. For every reaction, the target was positioned at the end of the beam line in the west experiment area. After the beam was cut off, gamma-ray spectra of the decay products were measured. By measuring the area under the gamma-ray peak corresponding to the decay of the reaction product, the production yields were determined. The dose rate of the residual activity was measured using a flat probe Geiger counter placed underneath the target at a distance of 46 inches.

Results of these measurements are detailed in the table below. The last column in the table gives the value of maximum dose rate of the activity generated when the beam was incident on the target. For comparison, production rates calculated using empirical equations and the available experimental data[7] are shown (column 4 of the table).

Table 1.7. Production rates and dose rates when 25 MeV proton beams are incident on various thick targets

Target	Final Product	Yields measured	/sec/nA Calculated	dose rate mrem/hr/nA @ 1 meter
ZnO	^{64}Ga	1.56×10^6	1.69×10^6	9.72
Zn	^{64}Ga	1.17×10^6	2.16×10^6	5.89
Zn	^{63}Ga		8.42×10^5	5.89
ZnO	^{63}Ga		6.58×10^4	9.72
CeS	^{34}Cl	9.35×10^3	6.56×10^4	7.91
S	^{34}Cl		2.40×10^5	7.10
Zr_5Ge_3	^{69}As		5.59×10^4	5.16
Zr_5Ge_3	^{70}As		5.81×10^5	5.16
Ni	^{59}Cu		1.13×10^5	4.86
Ni	^{60}Cu		7.91×10^5	4.86
Ni[a]	^{58}Cu	5.63×10^5		4.86

[a]Due to lack of sufficient experimental data empirical calculations are not possible.

1. Louisiana State University, Baton Rouge.
2. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
3. Vanderbilt University, Nashville, TN.
4. INFN/LNS, Catania, Italy.
5. Georgia Institute of Technology, Atlanta.
6. Mississippi State University, Mississippi State.
7. Numerical Data and Functional Relationships in Science and Technology, by Landolt Börnstein.

TEMPERATURE AND EVAPORATION TESTS OF POTENTIAL RIB TARGET MATERIALS

J. Kormicki,[1,2] *H. K Carter,*[1] *J. B. Breitenbach,*[1] *K. Jentoft-Nilson,*[3] *A. H. Poland*

A number of potential target materials for radioactive ion beam (RIB) production at HRIBF have been tested on the UNISOR separator to collect information on how they will behave in conditions similar to those existing in the ion source. The tests were performed in a bell jar, in a target material test stand, and in FEBIAD and EBP ion sources. The following target materials were tested in a bell jar for the melting point and mass losses (indication of extensive vaporization): Al_2O_3, Ga_2O_3, ZnO, MgS, and CeS. The influence of target materials on the performance of the ion source was studied for BeO, BN, CeS, Al_2O_3, and Zr_5Ge_3. Xe was used to monitor the ion source performance. More detailed tests were performed in the ion source on: NiO, NiAl, and Zn. Table 1.8 summarizes the results.

Table 1.8. Summary of target material tests

RIB Species	Target Material	Target Melting Pt. (°C)	Operating Temperature (°C)	Comments
^{10}C	BN	sublimes 3000	1700	Stable on-line
	AlB_2			killed ion source
$^{14,15}O$	BN	sublimes 3000	1700	stable on-line
$^{17,18}F$	Al_2O_3 (solid)	2045	< 1700	unstable under beam
	BeO	2578	1700	off-line O.K.
^{30}S	SiO_2	1435	1200	off-line O.K.
	Zr_5Si_3		< 1600	poor Xe efficiency
^{34}Cl	CeS	2450	1900	stable on-line
	MgS	> 2000	< 1700	killed ion source
^{58}Cu	NiO	1984	1400	poor efficiency corrodes Ta
	Ni	1455	> 1400	Ion source/target stable
	NiAl		1300	corrodes Ta
$^{63,64}Ga$	ZnO	1969	1100	poor Xe efficiency corrodes Ta
	Zr_3Ge_3	2500	1800	poor Xe efficiency
$^{69,70}As$	molten Ge	940	1100 – 1300	stable Xe efficiency

The vacuum, purity of sample, and interaction with crucible material can have a significant influence on the behavior of target materials in the ion source and can seriously limit the applicability of some target materials. BeO, BN, CeS, and Al_2O_3 showed no significant influence on FEBIAD ion source efficiency up to about 1700° C operating temperature. NiO in a Ta boat tested in the MARK1 ion source showed no influence on ion source efficiency up to 1400° C; however, it corroded the Ta boat. In a graphite boat, NiO operated safely up to 1400° C. The NiAl target in a graphite crucible was run in the target test stand up to its melting point at 1375° C. At this temperature the vaporization rate is 3×10^{-7} g/sec. NiAl was also run in the MARK1 ion source in a Ta boat and showed a drop of ion source efficiency starting at about 1400° C. At 1600° C, the ion source efficiency drop is significant, and, at this temperature, NiAl forms a low temperature alloy with Ta and melts the target holder. The maximum operating temperature for NiAl in a graphite target holder is estimated to be about 1300° C. ZnO has been tested in a MARK1 ion source in Ta and Re boats up to temperatures around 1100° C. ZnO, run previously in the bell jar, showed significant mass loss, and, even below 1100° C, ion source efficiency was reduced significantly. ZnO also reacted with Ta boat.

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3. Georgia Institute of Technology, Atlanta,.

ACTIVATION AND SUBSEQUENT RELEASE OF POTENTIAL RIBS FOR HRIBF

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Activation/release experiments for possible radioactive ion beams have been performed at the UNISOR mass separator. Once a target material is determined to be usable in an ion source, measurement of the release time and efficiency of the reaction products from the target material is the next critical step. The assumed mechanism is that atoms produced in nuclear reactions diffuse to the target surface and then evaporate into the ion source volume, where they may undergo ionization. Both diffusion and evaporation depend strongly upon target temperature (see also "Temperature and Evaporation Tests of Potential RIB Target Materials" in this report). Experiments were performed using 25 – 40 MeV, 0.1 to 1 μA proton beams from ORIC and lower intensity proton and deuteron beams from the tandem on selected targets. After activation, the target was removed from the chamber and the intensity of gamma radiation associated with various reaction products (i.e., the potential radioactive ion beam) was measured using a Ge gamma-ray detector. The activated target was then placed in the material test stand and heated to the desired temperature. After heating, the intensity of the same gamma radiation was measured and compared with the amount measured before heating with corrections for decay. The difference was used to estimate the percentage release for a given target temperature and time duration.

Table 1.9. Summary of activation/release experiments

Target material	Isotopes produced	Temperature	Release
NiO	$^{60,61}Cu$	1200° C	< .1%
Ge	$^{70,71,72,74,76}As$	1025° C	1%
Ge	$^{70,71,72,74,76}As$	1075° C	10%
Ge	$^{70,71,72,74,76}As$	1175° C	50%
Ni	$^{60,61}Cu$, ^{55}Co, ^{57}Ni	1330°C	< .1%
Al_2O_3 (solid)	^{18}F	1700° C	< .1%
Al_2O_3 (fibers)	^{18}F	1700° C	95%
ZnO	$^{66,67}Ga$	1300° C	< .1%

These results show no measurable release for Cu, Co, Zn and Ga. For As, the release increased with temperature up to 50% release at 1175° C. (Ion source with melted Ge target can operate successfully up to about 1400° C.) In this simple preliminary experiment, no effort was devoted to estimate the release as a function of time. For F, no significant release was observed from solid Al_2O_3 targets; whereas, for fibrous Al_2O_3 targets, greater than 80% release was observed when heated to 1400° C.

1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Vanderbilt University, Nashville, TN.
3. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
4. The University of North Carolina at Chapel Hill, Chapel Hill.
5. A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, CT.
6. Georgia Institute of Technology, Atlanta.

ON-LINE RELEASE EFFICIENCY AND TIME MEASUREMENTS ON POTENTIAL RIBS FOR HRIBF

J. B. Breitenbach,[1] H. K. Carter,[1] J.Kormicki,[1,2] S. Ichikawa,[3] A. H. Poland, J. C. Batchelder[4]

The on-line implantation and release studies have been performed at the UNISOR mass seperator to collect information about the target/ion source performance for selected beam/target combinations and to obtain data for selection of initial RIBs for HRIBF. The implantation technique developed by R. Kirchner[5] was used. The stable complements of potential RIB projectiles were produced in the 25-MV HRIBF tandem accelerator and implanted into the targets, or catchers, (Ta, C, BN) mounted in a GSI-type FEBIAD ion source on line with the UNISOR ion separator. The implanted species, after diffusion through the target material and effusion through the ion source, were ionized and mass separated. The separated ion current was measured as a function of time. The growth during the implantation time and decrease after the beam is stopped gives information about diffusion, ion source efficiency and sticking time in the ion source for the desired combination of projectile and targets. To measure possible background effects (e.g., beam heating, channeling) a second Faraday Cup monitors a second isotope of the accelerated mass. For example ^{63}Cu can be used as a background signal while implanting ^{65}Cu. Figure 1.33 shows release data for three beams implanted into a BN catcher. An unexplained effect is the large release observed when the As beam was turned off. This was as if As is stored in the BN catcher during implantation and released suddenly after beam is turned off (at 4500 sec for As, Se, and 500 sec for Cl). The Cl and Se curves are the expected behavior. A summary of results from these experiments is shown in Table 1.10.

Table 1.10. Results from implantation/release experiments

Beam	Separation Efficiency (%)	Upper Limit on Effusion Time (s)
As	9	300
Br	3.5	100
Cl	2.3	20
Cu	9	1
F	<.01	no information
Ga	23	3
Se	1.5	400

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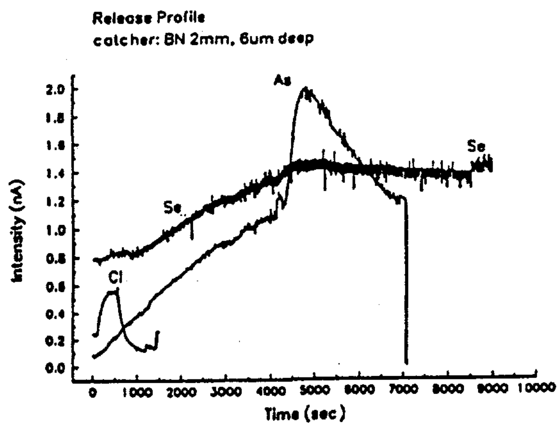

Fig. 1.33. Typical release profiles from stable beam implanted into BN catcher.

1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Vanderbilt University, Nashville, TN.
3. JAERI, Tokai-Mura, Ibaraki, Japan.
4. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
5. R. Kirchner, *Nucl. Instrum. Methods in Phys. Res.* **B70**, 286-299 (1992).

EXPERIMENTAL FACILITY DEVELOPMENT

COMPUTING INFRASTRUCTURE DEVELOPMENT

C. N. Thomas,[1] *R. L. Varner*

Networking: The Physics Division maintains distributed computing resources. Central to this strategy is a network which can accommodate the increasing number and higher performance of our workstations and personal computers. Several steps have been taken to improve the performance and reliability of the Physics Local Area Network (LAN).

The Physics LAN has been converted from a single flat network consisting of repeated segments to one which is divided into eight switched segments. A CISCO Systems Catalyst switch was installed to tie together the eight logical segments and connect them to the FDDI ring. The switch improves network performance by isolating traffic on the segments that the communicating devices use. This results in at least a 400 percent increase in available bandwidth.

Another network improvement was to subnet the Physics LAN. This was accomplished by installing a CISCO Systems C4500M router between the ORNL intraplant FDDI ring and the Physics FDDI ring. The router isolates the Physics LAN from unwanted traffic generated on the large ORNL network. Eliminating the high level of background broadcast traffic increased the available bandwidth and reduced the load that network traffic places upon the computers attached to the network.

Our FDDI network (ring) has been extended to provide faster network access for high performance workstations. The Physics FDDI (100 Mbits/sec) ring consists of fiber optic cables between Buildings 6000, 6003, 6008 and 6010 and DEC concentrator 500s in each building. Each concentrator can accommodate up to 12 workstations. When needed, fiber optic cables are run from the concentrator to the office where the FDDI equipped workstation resides. At the present time, there are twelve workstations connected to the Physics FDDI ring.

Computing: At the present time, there are 72 workstations in the Physics Division, most of which use UNIX operating systems. There are also 66 X-terminals that provide X-windows access to the workstations. Most of the X-terminals are color Tektronix 200 and 300 series. There are approximately 106 personnel computers (IBM clones) and 56 Macintosh computers.

During the past year, we invested in several substantial upgrades to the Silicon Graphics Power Challenge computer in the Physics Division. These included replacing the 4-R8000-processor board with two 4-R10000-processor boards, increasing the memory to one gigabyte and adding 36 gigabytes of disk driver. In addition, the high-energy reactions group has added a RAID disk system for use in their analysis of WA98 and other data.

Unfortunately, our experience with this upgrade has not been satisfactory. The primary theory group users of the machine have discovered that the R10000 processors are slower and that the compilers do not parallelize their code for these processors. As a result, we are considering our future options for high-performance computing in the division.

Printing: In keeping with our distributed computing policy, we operate 12 networked printers in the Physics Division complex. In general, they provide lp and lpd print services for the unix workstations using the Transcript software package to format and dispatch print jobs. Some also provide Localtalk and AppleTalk printing for Macintosh users. Two QMS Magicolor printers provide color laser printing with 600 dpi resolution. High speed laser printing (17 pages/minute) and duplex (dual sided) printing is provided by a QMS 1725 printer. A variety of HP, QMS and DEC printers are located near most work areas to provide low end (6 pages/minute) print service.

E-mail: Our electronic mail now uses only SMTP over Internet. BITNET is no longer supported since the BITNET network is defunct. There is also no support for DECNET mail since ORNL no longer supports DECNET connections to ESNET. We operate a central mail router that processes mail destined for the address "mail.phy.ornl.gov" and either routes it to the appropriate workstation or holds it for retrieval via POP mail service by PC and Macintosh users. Central mailing lists are maintained to handle the distribution of mail to various subgroups within Physics.

1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.

DATA ACQUISITION SYSTEM DEVELOPMENT

H. Q. Jin,[1] J. W. McConnell, W. T. Milner, R. L. Varner

The design and development of the Oak Ridge Physics Acquisition System, ORPHAS, has been reported previously.[2,3] Developments during this period include:

- Porting of ORPHAS to DEC3000 (Alpha) workstations
- Capability to record scaler data on tape at periodic intervals and at the end of each file
- Support for CAMAC modules having sparse readout features
- Conditional event readout based on parameter gates
- Support for readout of additional FASTBUS and FERA modules

ORPHAS has been ported to DEC Alpha workstations running Digital UNIX. This required changes in several codes due to differences in system calls between ULTRIX and Digital UNIX and differences in tape I/O. The source codes for the ULTRIX version and the Digital UNIX version have been merged using conditional compile statements. A single set of source codes supports both systems which eases maintenance and upgrading the system. However, the two systems require different Make files.

The capability to record scaler data on tape during acquisition has been added to ORPHAS. Most commercially available CAMAC scaler modules are supported. Scalers may be recorded at periodic time intervals and/or at the end of each data file. Readout specifications are read from a file which is compatible with the scaler display program SCAD. The scaler data records may be extracted from the data tape using LEMO.

ORPHAS now supports the use of sparse readout features available in several CAMAC modules. Since the readout format varies among manufacturers, users must specify the module type in their PAC program. The manufacturer's format is translated to L003 format by the VME system during readout. A complete list of the modules supported is available in the PAC documentation.

Gates may be defined for data parameters and results of the gate tests may be used (1) to reject events, (2) to count-down events, and (3) for conditional readout of FASTBUS, FERA and sparse format CAMAC modules.

New FASTBUS modules have been added for the BaF_2 array and a new FERA readout module has been added for use with the Double-Sided Silicon Strip Detector. ORPHAS supports these new modules.

We currently have six systems which can support data acquisition although not all systems are available for general use. A list of systems is given below along with the use normally associated with each.

Host-name	Platform	Normal-use
orph38	DECstation	Development, HiLi detector
orpas2	DECstation	Portable, general use
orpas3	Alpha	BaF array
rms1	DECstation	RMS control system
rms4	Alpha	RMS data acquisition
astro4	Alpha	DRS control system

DRS denotes the Daresbury Recoil Spectrometer currently being installed here. It should be noted that data acquisition can be run on the same system that provides for the control of either the RMS or DRS.

1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. J. W. McConnell et al., *Phys. Div. Prog. Rep. For Period Ending Sept. 30, 1992, ORNL-6746*, p. 15.
3. J. W. McConnell, *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1994, ORNL-6842*, pp. 2-25.

RECOIL MASS SPECTROMETER CONTROL SYSTEM

J. W. McConnell, W. T. Milner, J. W. Johnson[1]

The control system for the Recoil Mass spectrometer (RMS), first reported in 1994,[2] has been completed, extensively tested, and is in routine operation. This system utilizes a host workstation running UNIX connected to a VME based front-end via a private Ethernet. The function of this system is to control and/or monitor devices associated with the RMS; included are four high voltage (HV) power supplies associated with two electrostatic dipoles, 12 magnet power supplies, 12 Teslameters and a number of vacuum gauges. A list of the major control system hardware is given below.

Device	Function or use
DECstation 3000/125	Host workstation
FORCE-CPU-40	VME processor
DATEL-626 6-chan, 16-bit DAC	HV voltage set points
DATEL-628 8-chan, 12-bit DAC	HV current set points
DATEL-613 16-chan, 16-bit ADC	HV voltage readout HV current readout
ACROMAG-9480 64-bit I/O Reg	HV status
VMIC-6015 4-port serial I/O	Monitor & control of Magnet power supplies Teslameters Vacuum gauges
Green Springs Comp. VIPC610	Stepper Motor Controller

The multiprocess VME software which manages all hardware operations and communications with the workstation is essentially transparent to the user. The workstation software which directs the overall process and provides the human interface consists of two processes; RCON and RMON. RCON is primarily a user interface process and passes data to RMON via shared memory as required. RMON performs all real time repetitive monitor, control, display, logging and histogramming functions.

Main features of the system include:

- Automated conditioning of electrostatic dipoles
- Automated cycling and ramping of magnets
- Automated adjustment of magnet currents to achieve specified field values
- Automated setting of electrostatic and magnetic elements as required for a given ion, energy and charge state
- User controlled adjustment of elements coupled in a prescribed way via the KNOB command
- Selection of different modes of operation corresponding to different optical requirements
- Processing of files containing hardware configuration, mode, knob, field and calibration data
- Repetitive display and logging of electrostatic voltages, conditioning currents, magnet currents and fields, interlock status, vacuum gauges, etc.
- Finger positioning commands (see Note-1 below)
- Histogram records of all voltages, currents, magnetic fields and vacuum gauge readings

Note-1 Fingers: The charge state interception device used by the RMS consists of seven "fingers" each of which is driven by a stepper motor. A hardware multiplexor was designed to allow control of all seven stepper motors using a single VME controller module. Control hardware has been fabricated and tested. Routines for the stepper motors have been added to the RMS control task in the VME system. FORTRAN callable routines provide access to the hardware from the workstation. Software routines have been tested and documented but since cabling is incomplete, full integration into the control system has not been completed.

1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. J. W. McConnell et al., *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1994, ORNL-6842*, pp. 2-26.

HRIBF RECOIL MASS SPECTROMETER

D. Shapira, C. Gross,[1] *T. Ginter*[2]

A new Recoil Mass Spectrometer (RMS) has been installed and commissioned at the Holifield Radioactive Ion Beam Facility (HRIBF). Designed to detect rare events following heavy-ion, inverse kinematic reactions, the spectrometer will be the centerpiece of nuclear structure research at the HRIBF.

The RMS is a zero degree device which consists of two distinct optical systems with a large effective solid angle of ~ 13 msr and a 25 meter flight path. A momentum analyzer separates reaction products and primary beam resulting in a momentum focus inside of Q3. Because the primary beam has a well-defined momentum, small metal rods called "fingers" may be positioned to intercept the focused beam particles inside Q3 with minimal impact on the reaction products of interest. The seven "fingers" are independently operated and initial tests indicate at least a factor of 10 reduction in primary beam transmitted through the momentum separator. This results in improved detection capabilities for the smallest reaction channels.

The symmetry of the momentum separator allows the reaction products to be refocused at the achromat which acts as the object for the mass separator section of the RMS. The electric-magnetic-electric dipole combination separates nuclei independently of their energy as a function of their mass-to-charge ratio (A/Q). The large energy (± 10%) and A/Q (± 5%) acceptances allow multiple charge states of the same mass to be transmitted resulting in improved overall detection efficiency.

Other detection systems used in combination with the RMS allow the study of nuclei at the limits of stability with production yields of less than 0.001% of the total reaction cross-section. Double sided silicon strip detectors are used to detect protons emitted from implanted mass separated drip line nuclei. An array of clover germanium detectors, each consisting of four 25% efficient germanium crystals tightly packed in a single housing which can be operated singly or together, will significantly improve the detection efficiency of the in-beam γ ray spectroscopy and the β-decay spectroscopy measurements.

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1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.

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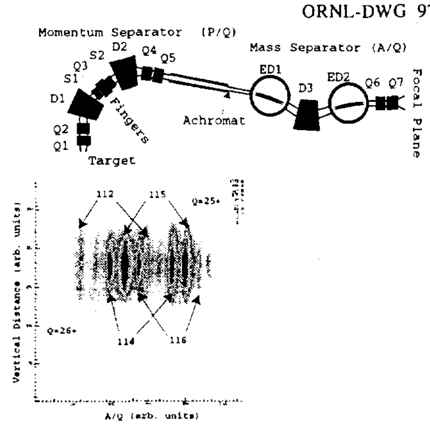

Fig. 1.34. (Above) Schematic of the RMS. (Below) A two dimensional spectrum of the reaction products detected at focal plane of the RMS. The data were taken with the reaction ^{58}Ni + ^{60}Ni at 220 MeV. Specific mass groups are identified. The mass resolution, defined as M/ΔM, is 450 and the mass dispersion is approximately 4.3 mm/%. There are no gating conditions on this spectrum. Note that there is little or no evidence of primary beam on the focal plane. Mass ambiguities can develop from the different A/Q combinations populated in the reaction as can be observed in the center where mass 116 and mass 112 lie close together.

RMS ALPHA TEST

T. N. Ginter,[1] C. J. Gross,[2] D. Shapira, W. T. Milner, Y. A. Akovali

We used a 1 mCi ^{244}Cm alpha source to calibrate individual elements of the RMS. Alpha particles from this source have an energy of 5.805 MeV. The alpha particles simulate reaction products with a well defined mass, energy, charge state, and position. The calibrations obtained from the test have served as the basis for scaling the RMS in later runs with beam.

For the test we placed the alpha source at two positions along the RMS: at the achromatic focus and at the target position. In each location we aligned the source along the RMS optic axis using a 1 mm aperture which also served to collimate the source. For electric and magnetic dipoles the goal of the test was to insure that the alpha particles followed the optic axis of the RMS as evidenced by the position of the alpha particles observed on the large PSAC placed at the final focal plane or on the mini-PSAC placed either inside Q3 or at the achromatic focus. For quadrupoles the goal was to tune the quadrupole doublets Q1-Q2, Q4-Q5, and Q6-Q7 to minimize the alpha particles spot-size observed while keeping it symmetric.

To tune the elements in the mass separator section of the RMS we placed the alpha source at the achromat and observed the position of the alphas on the large PSAC. We set D3 to its predicted value and sought the pair of E1, E2 settings that has two characteristics: (1) it delivers the alpha particles to the optic axis at the PSAC, and (2) it sends the alpha particle along the optic axis through quadrupoles Q6 and Q7. The test that the second requirement has been met is that no steering of the alpha particles occurs at the PSAC when we make large changes to the quadrupole settings. With Q6 and Q7 turned off we mapped out a set of points in E1, E2 space that delivered alpha particles to the optic axis at the PSAC. From this set we found the pair for which steering of the alpha particles was minimized with Q6 and Q7 turned on. See Figure 1.35. Using this matched pair, we then tuned the Q6-Q7 doublet.

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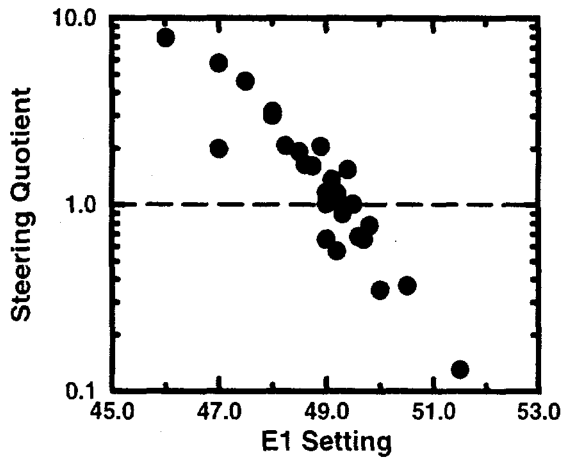

Fig. 1.35. Plot of steering quotient vs. E1 values in E1, E2 setting pairs which deliver alphas to the optic axis at the PSAC. The steering quotient is defined as the ratio of number of alphas on the left of the optic axis to the number on the right with Q6 and Q7 turned on divided by the same ratio observed with the quadrupoles turned off. Thus, a quotient of one indicates minimal steering.

For tuning D1 we placed the alpha source at the target position and the mini-PSAC at Q3. We found the D1 value that steered the alpha particles to the center of the mini-PSAC. We used this same configuration to tune the Q1-Q2 doublet. For tuning D2 we moved the mini-PSAC to the achromat. Using the settings we found for Q1, Q2, and D1 we sought the D2 setting that put alphas at the center of the mini-PSAC. We used this same setup to tune the Q4-Q5 doublet.

Finally we checked the entire system by allowing the alpha particles to pass from the target position all the way through to the PSAC at the final focal plane.

1. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.

2. Oak Ridge Institute for Science and Education, Oak Ridge, TN.

RMS ENERGY ACCEPTANCE

C. J. Gross[1] and T. N. Ginter[2]

The RMS is designed to have an energy acceptance for central particles of ± 10% with some recoils able to make it through with energy deviations of up to ± 15%. The length of the plates on the electric dipoles, which were designed to handle reactions producing recoils of high rigidity, limits the RMS energy acceptance. To verify the energy acceptance, we varied the scaling of the RMS to accept recoils of higher or lower energy without making any changes to the mass or charge state settings, using the ^{60}Ni (^{58}Ni, xpyn) reaction with a beam energy of 220 MeV and a target thickness of 300 μg/cm^2. We scaled the RMS to a central ion of ^{114}Te and a central charge state of 25.5. We varied the RMS to accept central recoils with energies from 90 to 116 MeV.

Using stopping power calculations we estimated the central recoil energy for this reaction to be 100.8 MeV. The fact that we observed a peak in the focal plane PSAC count rate at an energy of 102 ± 2 MeV confirms the reliability of our calculations. The count rate dropped to 50% of the maximum value at approximately 91 and 112 MeV which agrees with the designed energy acceptance.

Figure 1.36 shows the x-projection of the image obtained from the final focal plane PSAC with the RMS scaled to a central energy of 103 MeV. It also shows the x-projections obtained for the energies of 90 and 116 MeV, which more than span the energy acceptance of the RMS. The three spectra were taken over approximately equal time periods. The number of counts obtained in the spectrum for 103 MeV was higher than the numbers obtained in the other two because these other spectra are both on the edge of the recoil energy distribution. For comparison we normalized the 90 and 116 MeV spectra by multiplying them by factors of 2.44 and 2.56, respectively, so that each of the three spectra would have the same number of total counts. Note that the peak centroids do not shift and the peak widths do not change over this large range of energy. The RMS does what it is supposed to do: it delivers recoils of different energies to the final focal plane without dispersing them according to their energy.

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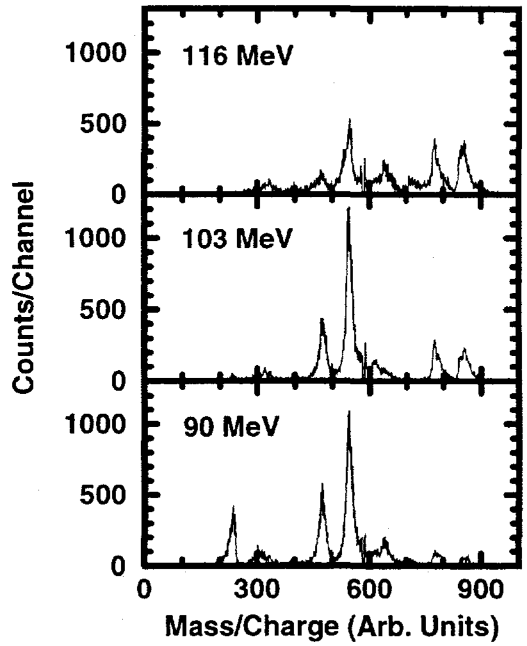

Fig. 1.36. Focal plane PSAC x-projections of the recoil data from ^{58}Ni on ^{60}Ni with the RMS scaled to the energies indicated.

Each energy spectrum in the figure corresponds to a specific RMS setting which transmits recoils with a given rigidity. In terms of recoil mass m, recoil velocity v, and recoil charge state q, the magnetic rigidity k is given by $k \propto m^2v^2/q^2$. Assuming constant mass, recoils delivered to the left side of the focal plane have energies higher than the central recoil while those to the right have lower energies. Thus, the changes in recoil intensity observed across the focal plane in the figure are due to the recoil energy distribution. For maximum production, the total recoil energy distribution should be matched to the RMS energy acceptance.

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1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.

RMS A/Q ACCEPTANCE AND MASS RESOLUTION

C. J. Gross,[1] T. N. Ginter,[2] D. Shapira

Figure 1.37 shows the x-projection of the recoil distribution we observed using the PSAC at the final focal plane of the RMS for the ^{60}Ni(^{58}Ni,xpyn) reaction at 220 MeV with a target thickness of 300 μg/cm^2. We scaled the RMS for central recoils of ^{114}Te at 103 MeV and charge state 25.3$^+$. This plot illustrates the mass resolution and the A/Q acceptance of the RMS. We did not make use of the fingers to obtain this data.

The overall mass resolution M/ΔM calculated from this mass spectrum is 450. (For example, the charge state 26$^+$, mass 115 peak has a FWHM of 19 channels; this peak is 78 channels away from its mass 114 neighbor, resulting in a mass resolution of 470.) The calculated mass resolution approaches the design value of 540. The predicted mass resolution of the RMS exceeds 1000 with the use of an appropriate collimator at the achromat and a software correction to the observed positions of the recoils. We obtained the present data without making use of either of these enhancements.

The RMS is designed to have an A/Q acceptance of ± 5%. The lower limit of recoils present in the data shown in the figure is 4.27 A/Q and the upper limit is 4.70 A/Q. This is a spread of ± 4.9% from a central value of 4.48 A/Q.

ORNL-DWG 97-5432

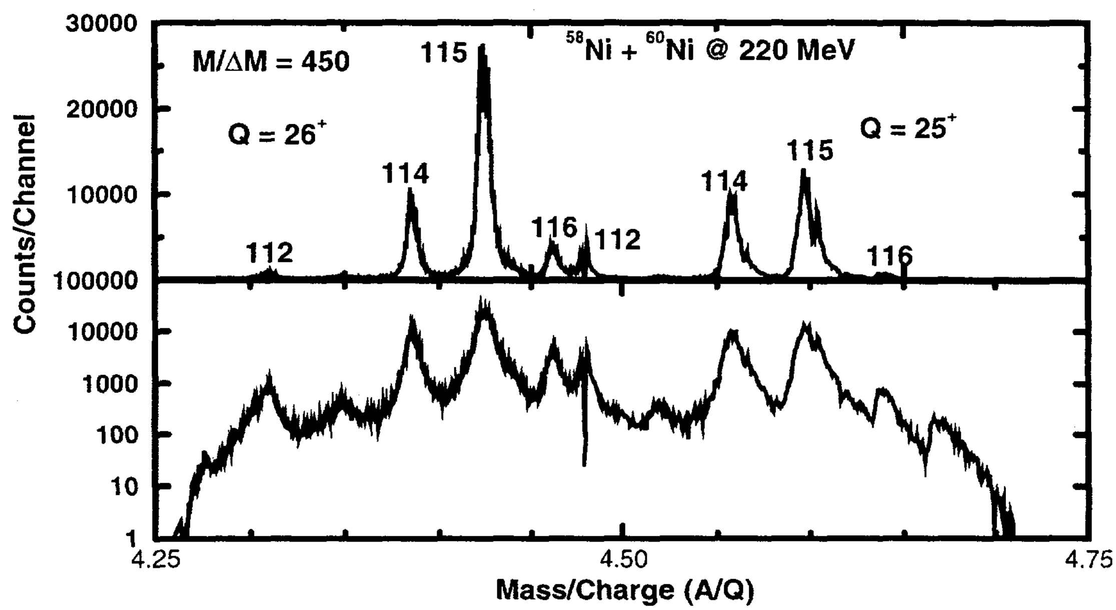

Fig. 1.37. Top: The x-projection of the recoil distribution obtained at the focal plane PSAC with the RMS scaled for a central recoil of ^{114}Te at a charge state of 25.3$^+$ and an energy of 103 MeV. Bottom: The same spectrum as above but on a log scale to highlight the A/Q acceptance.

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1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.

INITIAL TEST OF RMS FINGERS

T. N. Ginter,[1] C. J. Gross,[2] J. W. Johnson,[2] J. W. McConnell, D. Shapira

The RMS fingers are seven 2 mm diameter rods that can be moved independently to any position across the momentum focal plane in the middle of Q3. They are used to intercept the narrowly focused groups of beam particles of various charge states beam while having a minimal impact on the recoils which, because they do not have a well defined momentum, are distributed across the Q3 focal plane. For inverse reactions the fingers are crucial for preventing beam particles from reaching the final focal plane, since high charge states of the beam fall within the RMS acceptance for inverse reaction products. We have successfully completed an initial test of the fingers.

For this test we used the inverse reaction $^{12}C(^{58}Ni,xpyn)$ with a beam energy of 220 MeV and a target thickness of 150 $\mu g/cm^2$. We scaled the RMS for central recoils of ^{64}Zn at a charge state of 22.3^+ and an energy of 176 MeV. A silicon detector was placed at the target position to monitor the beam count rate. With the mini-PSAC located at the achromat, we observed two groups of particles corresponding to two beam charge states. Figure 1.38 shows the results of our measurements.

The plot on the right shows the normalized count rate observed in the mini-PSAC as a function of a single finger position across the Q3 focal plane. (The finger moves from right to left across the focal plane as the distance units on the plot increase.) The two dips in count rate indicate the positions of the beam charge states 24^+ and 23^+.

The plot on the left side of the figure shows two normalized x-projections of particle positions as observed in the mini-PSAC. The peaks on the right are from the 24^+ charge state and the peaks on the left are from the 23^+ charge state. By using two fingers to block the 24^+ charge state, we have reduced the number of counts in the corresponding peak by 66%.

ORNL-DWG 97-5433

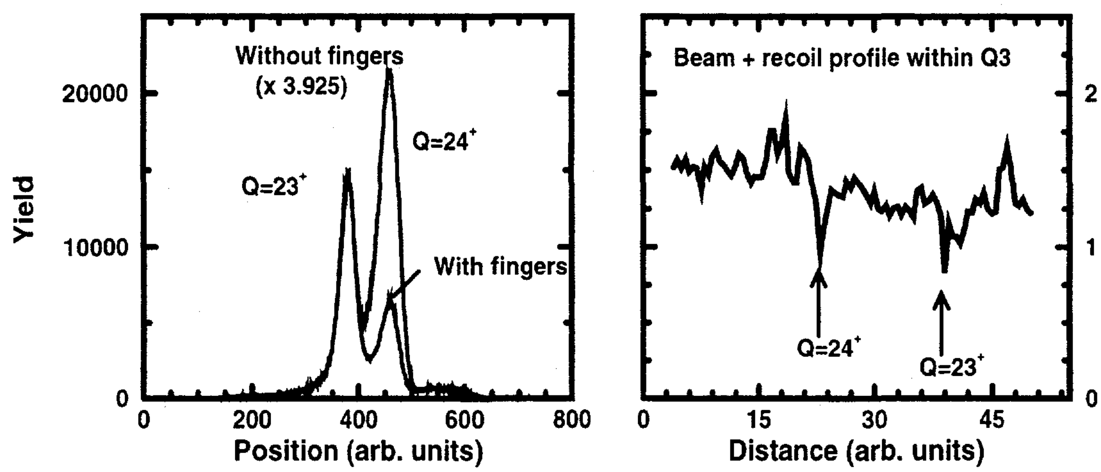

Fig. 1.38. Left: Horizontal position spectra observed with the mini-PSAC at the achromat. The large peaks, corresponding to charge states of the primary beam, dominate the data. By using the fingers to intercept the beam inside Q3, 66% of those events associated with $Q = 24^+$ are removed. Right: The normalized count rate at the achromat as a finger is moved 7.5 inches across the momentum focal plane inside Q3.

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1. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.
2. Oak Ridge Institute for Science and Education, Oak Ridge, TN.

MASS IDENTIFICATION OF A = 86,87 NUCLEI VIA PROMPT γ-RAY EMISSION

M. J. Brinkman, T. Ginter,[1] C. J. Gross,[2] D. Shapira

Prompt γ–ray spectra were collected at the target position as part of commissioning the recoil mass spectrometer (RMS). The γ–ray detectors were installed to perform two functions. First, γ–ray detectors provide a useful diagnostic tool for studying the interactions at the target position. In this case one uses the differences in γ–ray emissions arising from beam–target interactions and γ–rays emitted following interactions of the beam with various materials surrounding the target. The second, and primary, purpose of the γ–ray detectors was to provide a means of assigning the masses of recoil groups detected at the focal plane.

This RMS commissioning experiment used a 120–MeV beam of ^{32}S bombarding a thin (i.e., ~300 μg/cm^2) self–supporting foil of ^{58}Ni. The two most intensely populated reaction channels in this experiment were ^{87}Nb and ^{86}Zr populated following the evaporation of three and four protons, respectively. These recoils required ~2.5 μs to travel the 25 m flight path of the RMS.

During this run, four Compton–suppressed germanium detectors were installed at the target position. These coaxial detectors had a relative photopeak efficiency of ~25% (compared to that of a 3" × 3" cube of NaI measuring 1332–keV γ rays), and were situated ~15 cm from the target. The Ge detectors were surrounded by bismuth germanate shields which served to suppress the detection of Compton–scattered γ rays. In Figure 1.39, below, a total projection of RMS events and Ge coincidence spectra collected during a portion of this run are provided.

ORNL-DWG 97-5430

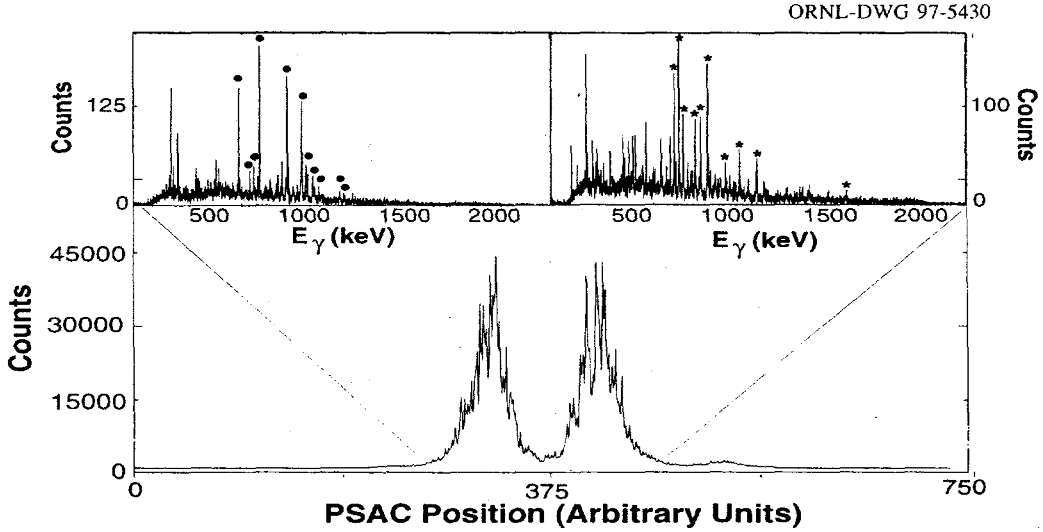

Fig. 1.39. Experimental data collected during three hours of the RMS commissioning run described in the text. The main figure shows the x–projection of the position–sensitive avalanche counter (PSAC) located at the RMS focal plane. The left (right) inset shows the Ge spectra in coincidence with the left (right) large recoil group as defined by the lines. The • (*) denote known strong transitions in ^{86}Zr (^{87}Nb). The unlabelled transitions in each spectrum correspond to weaker lines in the same nuclei and transitions from other nuclei with the same masses.

1. Vanderbilt University/University-DOE Laboratory Cooperation Graduate Student Research Participation Program.
2. Oak Ridge Institute for Science and Education, Oak Ridge, TN.

RMS FOCAL PLANE DETECTOR—POSITION SENSITIVE AVALANCHE COUNTER

C J. Gross,[1] D. Shapira, J. Batchelder,[2] J. W. Johnson,[1] J. Blankenship,[3] D. Rudolph,[4] A. Poland

The focal plane detector of the RMS is a Position Sensitive Avalanche Counter (PSAC). This is a gas filled detector comprised of four wire planes constructed on 3.175 mm PC board. The back of each board is milled out to half thickness to allow tight packing of the boards. Gold plated tungsten wire 20 μm thick is soldered in place. The high voltage planes have wire 1 mm apart and are electrically but not physically separated in half. The x-sense plane is also electrically cut in half but the wire separation is 2 mm. The y-sense plane is not divided and has 2 mm wire separation. Each wire on the sense planes leads to a string of delay chips such that each successive wire is separated in time by 2 ns. Position, and hence the mass of the ion, is determined by the time delay recorded between the anode signal and the sense planes. Both left and right (top and bottom) signals are digitized and their difference determines the position of the ion.

The detector has an active area of 36 cm x 10 cm and the volume is filled with approximately 3 torr of isobutane gas. The gas is continuously circulated but not recycled. Two 0.9 μm mylar windows are supported by ~ 50 μm wires approximately 5 cm apart. The detector has been operated reliably with a configuration with respect to the beam of cathode, x-sense, anode, and y-sense planes. For alpha particles, operating voltages are -230 V and +480 V. The rise time of the amplified (x100) anode signal is of the order of 10 ns with a pulse height of 250 mV. The position signals are of similar quality but their height is reduced due to the delay line and the double end read-out. The cathode signal is visible but of poor quality.

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1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Louisiana State University, Baton Rouge.
3. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
4. Oak Ridge Institute for Science and Education, on assignment from the University of Göttingen, Germany.

ORNL-DWG 97-5430

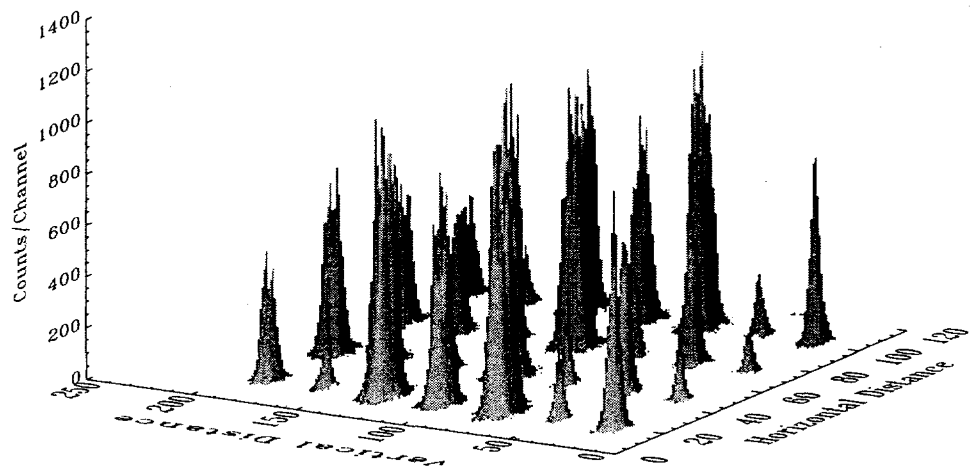

Fig. 1.40. The two dimensional focal plane of the RMS covered by a mask of 1-, 2-, 3-, and 4 mm holes with position resolution of less than 2 mm.

RMS FIELD SCALING

A. N. James,[1] W. T. Milner, T. N. Ginter[2]

Figure 1.41 illustrates how the RMS control system determines the settings for the individual elements based on two categories of input. One category is user input to specify the mode, the recoil (the ion or its mass, its charge, and its energy), and knob settings. The second category of input is system parameters.

The control software starts the calculation with a set of basic field values which is determined by the mode selected. The basic field values are the calculated element settings required to deliver recoils of mass 100, energy 100 MeV, and charge state 10^+ through the spectrometer in a manner that meets the design objective for the mode. These settings were calculated using the ion-optical code GIOS.[3]

The control software converts the basic field values into adjusted basic field values which take into account any user-requested knob settings. For a given element the adjusted basic field value F_A is calculated from the basic field value F_B using the formula

$$F_A = F_B + \sum_i s_i k_i$$

where the index i is the knob number, the s_i are the user knob settings, and the k_i are knob coefficients. (Knob coefficients define the knobs available and how they work; they can differ from mode to mode.)

The control software next converts these adjusted basic field values into recoil specific field values, i.e., the element settings necessary to deliver recoils other than those of mass 100, energy 100 MeV, charge state 10^+. The magnetic fields B and the electric fields E are scaled according to the relations

$$B \propto \frac{\sqrt{mT}}{Q} \qquad\qquad E \propto \frac{T}{Q}$$

where m is mass, T is kinetic energy, and Q is charge.

Finally the control software applies system-defined calibration parameters to convert from the recoil specific field values to calibrated field values. The calibrated field values are the element settings necessary to make the device actually perform in accordance with the predictions from the ion optical calculations. (We obtained the calibration parameters during commissioning runs.) For a particular element, the calibrated field value F_C is calculated from the recoil specific field value F_R by

$$F_C = A + BF_R$$

where A and B are the system supplied calibration coefficients.

ORNL-DWG 97-5436

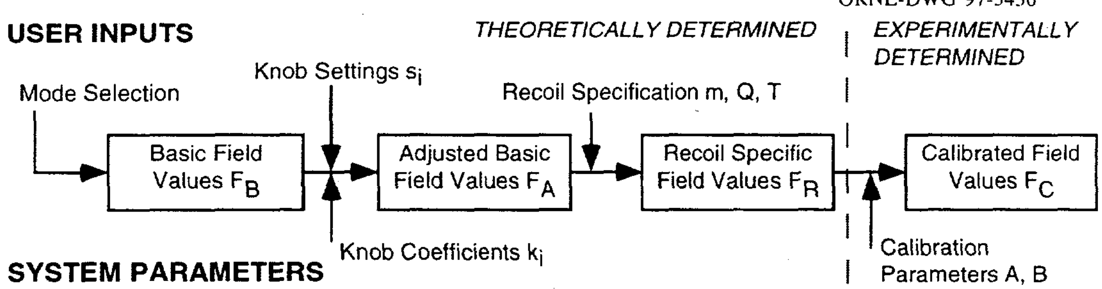

Fig. 1.41. Summary of calculations performed by the control software to determine element field settings.

1. Liverpool University, Liverpool, United Kingdom/JIHIR, Oak Ridge, TN.

2. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.

3. H. Wollnik et al., GIOS – a program for the design of general ion-optical systems, II. Physikalisches Institut, Universität Giessen, D-6300 Giessen, Federal Republic of Germany.

MODES: A WAY TO DEFINE THE BASIC RMS SETUP

A. N. James,[1] *T. N. Ginter,*[2] *W. T. Milner*

The RMS can achieve different fundamental optical and experimental goals depending upon the way its elements are scaled with respect to each other. The term we use to describe one of these fundamental scaling schemes is "mode". The first step in operating the RMS is to choose the mode that best suits the intended application. Within each mode "knobs", which are described in a separate report, provide smaller changes for adjusting the setup or optimizing the performance of the RMS. Currently, two modes are available. More modes will be developed in the future as the need arises.

The first mode is the diverging mass mode. This mode is part of the original RMS design. The goal of this mode is to maximize the physical separation of different masses at the final focal plane. Recoils in different mass groups are diverging after they leave the focal plane PSAC; therefore, this mode may not be suited for experiments requiring the collection of different mass groups in a single small area after they pass through the PSAC. The bottom frames of Figure 1.42 show the recoil distribution in x and y at the focal plane PSAC generated in this mode. (Note that here we have optimized the knobs to give a narrow focus in the y direction to deliver as many recoils as possible from the central mass group onto a small detector placed behind the PSAC.)

The second mode available is the converging mass mode. The goals of this mode are: (1) to provide mass separation at the PSAC, and (2) to deliver as many recoil mass groups as possible to a small area behind the focal plane PSAC (e.g., the double sided silicon strip detector). In this mode the separated mass groups approach the optic axis after passing through the focal plane PSAC. The cost of operating in this mode is a smaller physical separation between the mass groups at the PSAC. In order to use this mode, the polarities of Q6 and Q7 must be switched. Development and testing of this mode is still in progress. The top frames in Figure 1.42 show the recoil distribution in x and y that this mode generates. Note that the recoils are spread over a smaller range in x than for the diverging mass mode.

ORNL-DWG 97-5525

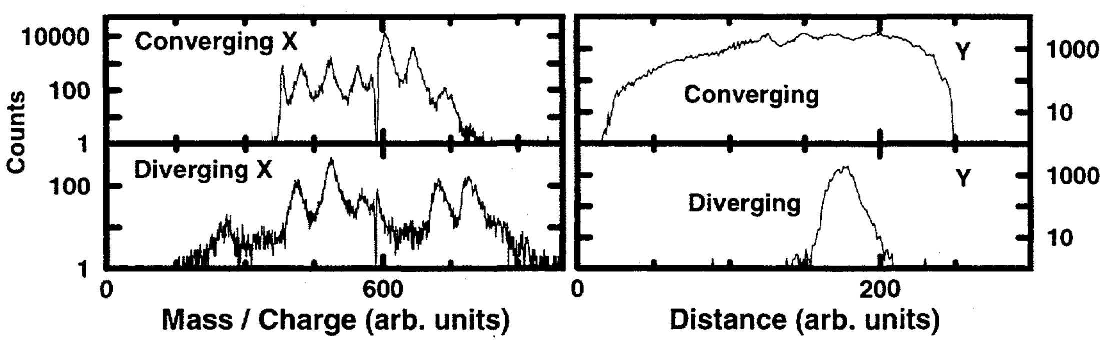

Fig. 1.42. Distribution of recoils obtained for the diverging and converging mass modes. The recoils in the diverging distribution are from the $^{60}Ni(^{58}Ni,xpyn)$ reaction, while recoils in the converging distribution are from the $^{58}Ni(^{32}S,xpyn)$ reaction.

1. Liverpool University, Liverpool, United Kingdom/JIHIR, Oak Ridge, TN.
2. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.

KNOBS: A TOOL FOR ADJUSTING THE RMS

A. N. James,[1] W. T. Milner, T. N. Ginter,[2] J. Mas[3]

Knobs provide users a convenient way to select among RMS observables in order to optimize the device to meet the needs of a particular experiment without requiring an intimate knowledge of the optics involved. RMS observables include such items as transmission efficiency, mass resolution, and vertical focus of the recoils at the final focal plane. The knobs presently available have been used in tuning the RMS. Users can also use these knobs to alter some details of operation. For example, these knobs may make it possible to fit the ion distribution into a given detector.

In general, different subsets of the 14 RMS elements affect different observables. For example, Q6 and Q7 determine the mass dispersion of recoils at the final focal plane. Another example is that the adverse effects of small changes in target position can be corrected by adjusting Q1 and Q2. It is possible to optimize an observable by adjusting the various subsets of elements without significantly affecting other aspects of the RMS performance. Table 1.11 lists the currently available knobs and the observable properties they affect; it shows which knobs operate on which elements.

The RMS control system implements knobs through system-defined coefficients and user-specified settings. The system-defined coefficients determine what elements are affected by a given knob and the relationship between the elements that must be preserved when the knob setting is changed. These coefficients were determined on the basis of optics calculations. User specified settings (ranging between 0.00 and 10.00) determine the strength of a knob's effect. (A setting of 0 turns any knob off.) Development of knobs is an ongoing process; knobs will be added as needed.

Table 1.11. Summary of the knobs available in the diverging mass mode for adjusting the RMS. Elements which are strongly affected by a knob setting are marked by "X", while those which are weakly affected are marked by "•". Note that knobs are mode specific.

Knob	Knob Purpose	Q1	Q2	D1	S1	Q3	S2	D2	Q4	Q5	E1	D3	E2	Q6	Q7
1	mass resolution								X	X					
2	vertical transmission [a]	X	X												
3	second order correction [b]				X		X								
4	second order correction [c]				X		X								
5	target-Q1 distance	X	X												
6	mass dispersion								•	•				X	X
7	vertical focus								•	•				X	X
8	vertical transmission[d]								X	X				X	X
9	horizontal focus at fingers	X	X		X		X		X	X					

[a] primarily affects transmission through D1 and D2
[b] for x aberration (X, AD) related to initial ion energy and angle in horizontal plane
[c] for x aberration (X, DD) related to initial ion energy
[d] primarily affects transmission through D3

1. Liverpool University, Liverpool, United Kingdom/JIHIR, Oak Ridge, TN.
2. Vanderbilt University/University-DOE Laboratory Cooperative Graduate Student Research Participation Program.
3. SERS program participant through Oak Ridge Institute for Science and Education.

A GRAPHICAL USER INTERFACE FOR USE IN PLANNING EXPERIMENTS USING THE RECOIL MASS SPECTROMETER
A Student Project

G. Gunderson,[1] D. Rudolph,[2] C. J. Gross,[3] M. J. Brinkman

Optimizing Recoil Mass Spectrometer (RMS) experiments is a delicate process that involves making a number of trade offs in competing experimental parameters. For example, one can increase the production of the desired nuclei by increasing the thickness of the target. Increasing the target thickness, however, causes a concomitant decrease in the detection efficiency of the RMS due to the increase in multiple scattering of the recoils. We have developed a graphical user interface that combines various computer codes that will aid users in planning RMS based experiments.

This user interface is written in the Tcl/Tk[3] language as a wish (i.e., WIndowing SHell) script. This script is executed through a wish interpreter which creates pipes to pre–existing codes that carry out the calculations. To use our application, one starts by entering the target A and Z, the projectile A and Z, the energy of the beam, the thickness of the target, and the Z and A of the desired residue. From these parameters the code then calculates the kinematics of the desired reaction. After this calculation the users are provided with the ability to calculate and plot any of seven useful quantities.

(1) The charge–state fraction of the reaction.
(2) The mass–to–charge ratio of the desired residue and competing channels.
(3) The Rutherford scattering of the beam.
(4) The slowing of the beam and recoil through the target.
(5) The multiple scattering of the recoils caused by the target.
(6) The range of the recoils in an ion chamber or DSSD at the focal plane.
(7) An estimate of the γ–ray count rate at the target position.

ORNL-DWG 97-5526

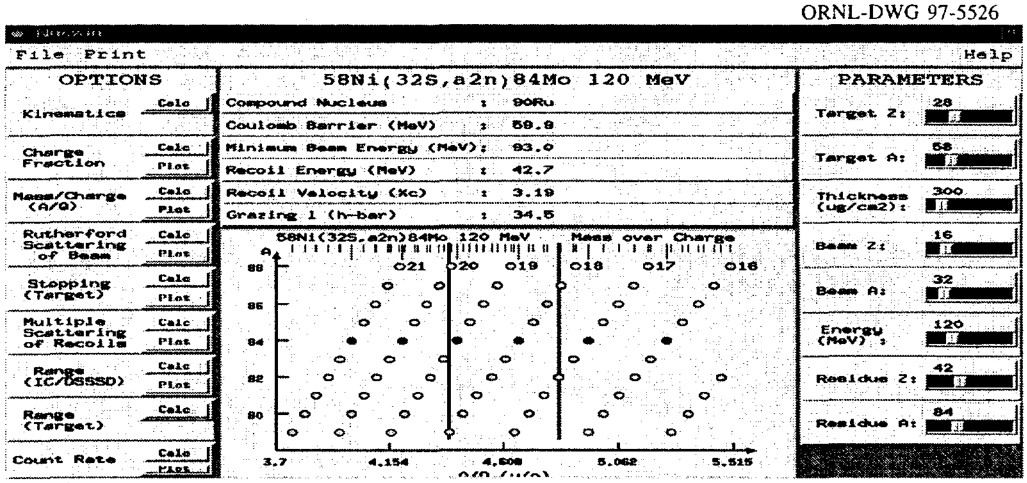

Fig. 1.43. A grey–scale version of the main window of the user interface for planning RMS based experiments. Immediately below the menu bar are three sections accessed by the user. The sections are (from left to right): (1) The Options window, containing a box for each calculation program, and buttons that calculate and plot the quantities, (2) The Plot window displaying the reaction kinematics and a graph corresponding to the current plot request (in this example a Mass/Charge plot), and (3) The Reaction window, where users enter the important experimental parameters for their proposed reaction.

1. Regional Teacher Research Associate from the Alabama School of Fine Arts.
2. Oak Ridge Institute for Science and Education, Oak Ridge, TN, on assignment from the University of Göttingen, Germany.
3. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
4. J. Ousterhout, *Tcl and the Tk Toolkit*, Addison–Wesley Publishing Company, 1994.

CONSTRUCTING A USER INTERFACE FOR THE RECOIL MASS SPECTROMETER

M. J. Brinkman and T. Ginter[1]

The Recoil Mass Spectrometer (RMS) is a complicated experimental device composed of twelve magnetic and two electrostatic elements. For users unfamiliar with the RMS, operating this device can be an imposing task for three reasons. First, the number of possible combinations of settings for the fourteen active elements can be overwhelming. Second, certain elements can be physically damaged by operating them beyond their designed limits. Finally, even when correctly set, the simple process of monitoring the status of the RMS can be daunting. We are implementing a user interface for the RMS designed to overcome these three difficulties.

The user interface to the RMS is written in the Tcl/Tk[2] language as a wish (i.e., WIndowing SHell) script. This script is interpreted through a wish interpreter modified to include the functionality of expect[3] and local commands designed to allow for reading the shared memory segment containing the current RMS parameters. The user interface functions by connecting to the RMS control shared memory segment and spawning a slave version of W. T. Milner's RMS control system, which can be both written to and read from using the expect extension.

The user interface was designed to implement a very limited subset of the full RMS control system. For example, the only means of setting active elements is to change the reaction parameters, the operating mode, and/or the knobs. All of the available commands are interlocked to ensure that they do not exceed the operational capabilities of the RMS elements. Requests meeting this criterion are rewritten to include all auxilliary commands that need to be undertaken (setting a current ramp rate, for example). This final group of commands is then sent to the slave process, where they are acted upon. The various RMS elements are continually monitored and their statuses are displayed through the use of a color code.

ORNL-DWG 97-5527

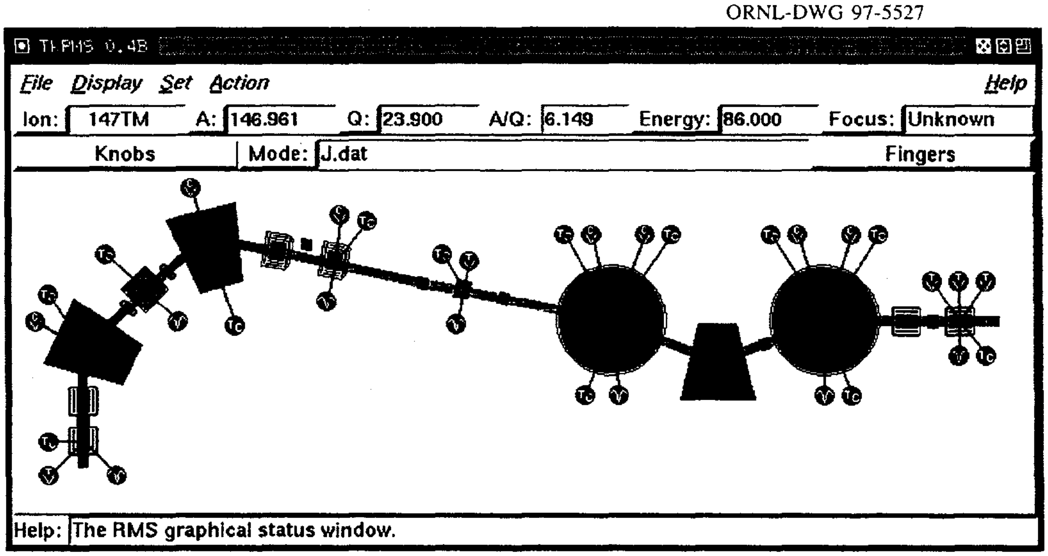

Figure 1.44. A grey–scale version of the main window of the RMS user interface. The five elements of this window (from top to bottom) are (1) the menu bar, (2) the reaction parameter line, (3) the knob, mode, and finger line, (4) the graphical status window, and (5) the help line.

1. Vanderbilt University/University-DOE Laboratory Cooperation Graduate Student Research Participation Program.
2. J. Ousterhout, *Tcl and the Tk Toolkit*, Addison–Wesley Publishing Company, 1994.
3. D. Libes, *Exploring Expect*, O'Reilly & Associates, Inc., 1995.

LIQUID NITROGEN CONTROL AND MONITORING SYSTEM
A Student Project

H. D. Sanders,[1] *J. W. McConnell, M. J. Brinkman*

A liquid nitrogen control and monitoring system for the germanium γ–ray detection array has been completed, tested on a small subset of detectors, and is awaiting final installation and complete testing. This system utilizes a host workstation running UNIX connected to a VME front–end via a private Ethernet. The function of this system is to control and/or monitor the liquid nitrogen filling system attached to the target–position germanium detectors. Included in this functionality is an interlock preventing the application of high voltage to the new Clover detectors until these detectors have been cooled. A list of the major control system hardware is provided below.

Device	Function or use
DECstation 3000/150	Host workstation
FORCE–68040	VME processor
VMIC–3413 x 2	Signal conditioning modules to acquire RTD currents
VMIC–3113A	ADC module to convert RTD currents to digital output
Acromag–9480	Digital I/O module to serve as a valve controller
VMIC–6015	Serial I/O to monitor and control high voltage mainframes

The front–end VME software performs all hardware operations and communications with the workstation and is essentially transparent to the user. Included in this functionality is the automatic filling of detectors based on the internal VME system clock. The workstation software is designed to direct the VME process and provides a graphical user interface. The graphical user interface is written in the Tcl/Tk language[2] as a wish (i.e., WIndowing SHell) script. This script is interpreted through a wish interpreter modified to include local commands designed to allow for the reading and writing of both a shared memory segment containing various control parameters and the VME front–end. The main features of the system include:

- Control/monitoring of up to 8 manifolds
- Control/monitoring of up to 32 valves
- Continual monitoring and display of up to 32 detector temperatures
- Automated filling of the detectors
- Dynamic definition of elements in the array
- Provide logging of all warnings, errors, and fills
- Definition of trip values for detector temperatures and filling times
- Definition of both filling and log file intervals
- Automatic reboot of system on power/communications failure(s)
- A convenient graphical user interface

1. Science and Engineering Research Semester Student from Cornell University.
2. J. Ousterhout, *Tcl and the Tk Toolkit*, Addison–Wesley Publishing Company, 1994.

DETECTORS AT THE TARGET POSITION OF THE RMS

C. Baktash, M. J. Brinkman, N. Gan,[1] C. J. Gross,[2] J. W. Johnson,[2] D. Stracener,[1] C.-H. Yu

In the early stages of the operation of HRIBF, stable and radioactive ion beams will be used to study the structure of nuclei near the proton-drip line. Due to both very small cross sections for the production of these far-from-stability nuclei and the relatively small intensities of RIBs, these studies will require very selective and efficient detector systems.

Because of its ability to select masses of the recoiling nuclei, the recoil mass separator (RMS) is expected to be used in the majority of these experiments. In the light and medium-mass nuclei, atomic number (Z) informaion is obtained from an ionization chamber located at the focal plane of the RMS. In the heavier nuclei, where an ionization chamber is not adequate, Z-information may be inferred by fully detecting the evaporation protons and alpha particles using a Hybrid charged-particle detector (Hyball) at the target position. Other target-position detectors include an upgraded Ge array and a set of neutron detectors at forward laboratory angles.

The Ge array will consist of 12 elements of the existing Compton Suppressed Spectrometer and 11 Clover detectors, as described elsewhere in this Progress Report. The Hyball consists of fast particle detectors covering laboratory angles of ~ 8-25 deg, and 80 CsI(Tl) detectors at more backward angles. The design and geometry of the CsI detectors follow those of the Washington University Microball.

Figure 1.45 shows the geometry of the target-position detectors, which is designed to reduce the exposure of the Ge and CsI detectors to the background of the 511 keV gamma rays and the positrons which result from the decay of the Rutherford-scattered radioactive ions stopped in the wall chambers or the absorbers. This background of radioactivity requires that the forward charged-particle detectors be placed at a large distance (~ 30 cm) from the target, and be fast enough to tolerate count rates of up to 20,000 Hz due to the positrons. We are currently investigating the suitability of plastic phoswich or microstrip Si counters for the forward elements of the Hyball.

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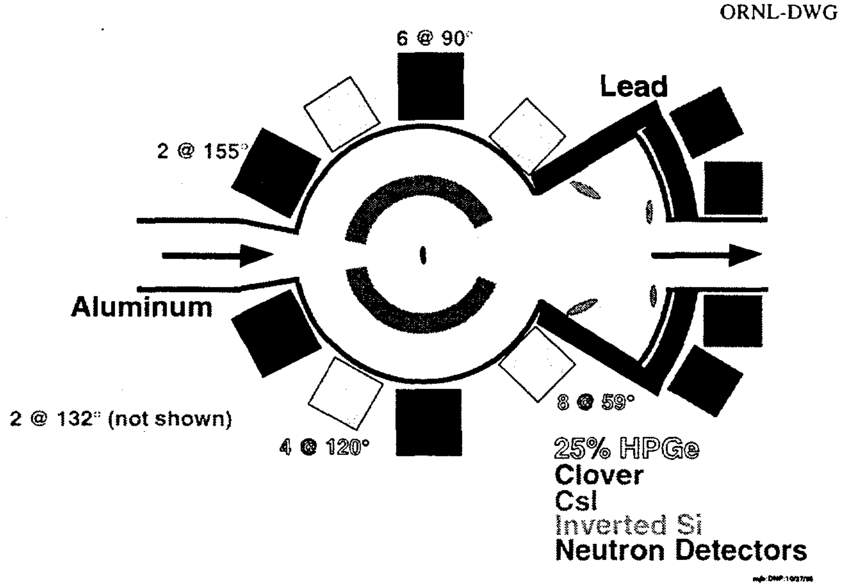

Fig. 1.45. Schematics of the geometry of the Ge, Hyball and neutron detectors at the RMS target position.

1. ORNL postdoctoral associate/Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Oak Ridge Institute for Science and Education, Oak Ridge, TN.

UPGRADE OF THE Ge-DETECTOR ARRAY

C. Baktash, J. R. Beene, M. J. Brinkman, J. W. Johnson,[1] P. Mantica,[1] J. W. McConnell, H. Sanders,[2] F. Starr,[3] M. Whitley, C.-H. Yu

The upgraded Ge-detector array[4] will be one of the major experimental tools at HRIBF to study structure of nuclei near proton-drip line. It will consist of 12 elements of the present Oak Ridge Compton Suppressed Spectrometer (CSS) and 11 Clover detectors. The Clover detectors are modified versions of those used in the Eurogam-II array. By nearly eliminating the dead layers between the adjacent crystals, the signals from all four crystals may be added together to obtain the total pulse height for an incident gamma ray that scatters from one detector to one or more of the other three detectors. This so-called add-back mode increases the total photopeak efficiency of a Clover detector by 50% at 1332 keV.

Compared to the Eurogam-II Clovers, the ORNL detectors have larger overall dimensions (8 cm long, approximately 8×8 cm^2 cross section) and are electronically segmented in the axial direction to achieve an effective transverse dimension of approximately 2 cm. Consequently, these detectors may be deployed very close to the target position without significant loss of energy resolution due to Doppler broadening effects. For example, for a recoil velocity of 5%, a segmented Clover located 15 cm from the target position achieves an energy resolution which is slightly better than that of a segmented Gammasphere detector placed at a target distance of 23 cm. The ORNL Clover detectors will be deployed at a distance of 19 cm from the target position to provide an absolute photopeak efficiency of nearly 0.3% per detector for a 2 MeV gamma ray. In its final configuration, the upgraded Ge array will have a total photopeak efficiency of ~4%. In addition to their large efficiencies and excellent energy resolution, Clover detectors may be used as polarimeters. The new support structure allows placement of up to six Clovers at 90° with respect to the beam direction for linear polarization measurements.

Of the 11 Clovers, six detectors have been purchased and will be available for experiments in early 1997. The remaining five Clovers will be procured in FY 98. Custom-designed electronics modules for the Clover detectors will become available in the fall of 1997. This module, based on the electronics circuitry developed for the Gammasphere project, performs all the analog and digital signal processing functions for a segmented Clover detector and its BGO Compton-suppression shield.

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1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
2. Science and Engineering Research Semester Student from Cornell University.
3. Science and Engineering Research Semester Student from Boston University.
4. Oak Ridge National Laboratory Gamma-Ray Detection Array Upgrade for Radioactive Ion Beam Studies Using the Recoil Mass Spectrometer, M. J. Brinkman, editor, a proposal to the U.S. Department of Energy, December 1994.

INSTALLATION OF THE ASTROPHYSICS EXPERIMENTAL STATION

J. C. Blackmon,[1] D. E. Pierce, D. W. Bardayan,[2] M. S. Smith, J. W. McConnell, A. E. Champagne,[1] P. D. Parker[2]

Reactions involving radioactive nuclei play a critical role in explosive stellar events, such as novae and supernovae. The experimental nuclear astrophysics program at HRIBF is centered on measurements of cross sections for these reactions using radioactive beams. A versatile experimental station for performing these measurements is currently being constructed. The station is built around the Daresbury Recoil Separator (DRS)[3] which will be used for the detection of recoil nuclei. An array of silicon surface-barrier detectors, based on the Louvain-Edinburgh Detector Array (LEDA) design, will be used for the detection of light charged particles, and the ORNL/TAMU/MSU array of BaF detectors will be used for detection of prompt gamma rays near the target chamber.

The DRS was transferred from Daresbury to ORNL in late 1994. The DRS separates recoiling reaction products from the incident beam with two **E**×**B** velocity filters and a 50° dipole magnet. There are also three sets of quadrupole triplet magnets for focusing and two sextupole magnets for correction of higher order aberrations. The DRS is well-suited to the measurement of capture reactions in inverse kinematics because of its 2-m-long velocity filters. For example, in the $^{17}F(p,\gamma)^{18}Ne$ reaction, the recoiling ^{18}Ne nuclei emerge from the target in a ± 0.5° cone with a momentum only 0.7% greater than the ^{17}F, but the separation between the ^{18}Ne and ^{17}F particles will be greater than 2 cm at the midpoint between the two velocity filters owing to the 5% velocity difference. We have used ion optical calculations to find a configuration of the system that improves projectile suppression. These calculations show it to be advantagous to run the velocity filters with opposite polarity, and with an additional horizontal focus between the two velocity filters. The DRS was installed in nearly the same geometry as used in Daresbury, but the distance between the two velocity filters was increased to allow for installation of a new chamber containing slits and beam diagnostics. The primary beam will be removed by these new slits, and beam scattered from the slits will be further reduced by the second velocity filter.

The physical installation of the separator is nearly complete. The 14 magnets have been installed and aligned. The magnet power supplies have been installed, converted to U.S. power, and interfaced to the VME control system. The magnet field is monitored by Hall probes and regulated by the control system software. In preliminary studies, the magnetic field resolution is on the order of 10^{-4}. The two velocity filter chambers have been rigorously cleaned, reassembled, installed, and aligned. The high voltage power supplies have also been installed, converted to U.S. power, and interfaced to the control system. The electrostatic plates have been raised to a voltage of 100 kV individually, and ± 60 kV together. A conditioning program is currently being developed to help automate further high voltage conditioning.

Two target chambers have been constructed for the DRS at the University of North Carolina at Chapel Hill and are currently being installed. One small chamber was built for close packing of external gamma-ray detectors, such as those in the BaF array, near the target. A second, larger chamber has been constructed for use with charged-particle detectors, in particular the LEDA silicon strip design. The two chambers mount on the same aligning base, and may be interchanged with relative ease. The annular LEDA array may be positioned up to 20 cm from the target, subtending $\Delta\theta \approx$ 20-30° in 16 segments. This gives a total efficiency of greater than 30% for (p,p) and (p,α) reactions.

The DRS focal plane detector system consists of a ΔE-E gas ionization counter and two carbon-foil, microchannel plate detectors. The ΔE-E gas ionization counter allows for clear mass identification up to mass 20, even at the low energies typical of our measurements. A time-of-flight technique may also be used in some cases for mass identification using the timing signal from the two microchannel plate detectors. The focal plane detector system has been tested in experiments at Yale University and is currently being transferred to ORNL. Once the focal plane detector system is installed, commissioning of the DRS with stable beams will begin.

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1. University of North Carolina at Chapel Hill, Chapel Hill.
2. Yale University, New Haven, CT.
3. A. N. James *et al.*, *Nucl. Instrum. Methods Phys. Res.* A **267**, 144 (1985).

ION-OPTICAL CONFIGURATION OF THE DARESBURY RECOIL SEPARATOR FOR NUCLEAR ASTROPHYSICS MEASUREMENTS

A. N. James,[1] D. W. Bardayan,[2] M. R. Roettger,[3] M. S. Smith, J. C. Blackmon[4]

To better understand stellar explosions, we will use the Daresbury Recoil Separator[5] (DRS) to measure (p,γ) absolute cross sections on proton-rich radioactive nuclei at HRIBF. The DRS is a large-acceptance (6.5 msr, ± 2.5 % in velocity), high-mass resolution (300), 14-magnet, 90-ton, 13 meter-long mass separator designed to detect weak channels in fusion evaporation reactions – where there is a large velocity difference between the beam particles ("projectiles") and the recoils of interest. The DRS was often used to collect multiple masses and charge states at the focal plane. In the inverse-kinematics (heavy-ion radioactive beam incident on a hydrogen target) proton capture reactions of interest in astrophysics, the projectiles and recoils have almost no difference in momentum, and differ in velocity by a few percent, in mass by one amu, and in intensity by 10^{10} – 10^{12}. In measuring (p, γ) absolute cross sections, we need to collect one mass group (the recoils) at the focal plane with the highest possible suppression of scattered projectiles. The viability of the use of recoil separators for these types of reactions was demonstrated with a smaller, non-optimized device at Caltech, where a projectile suppression of 10^{10} was achieved.[6] To boost the projectile suppression of the DRS, we are using ion-optics calculations to investigate configurations of the system which have a focus and aperture between the two 1.2 meter-long (crossed electric and magnetic field) velocity filters: this requires decoupling these devices and running them as separate spectrometers with opposite deflections. We have found two configurations suitable for our experiments – one is shown in Fig. 1.46, where the projectiles (with a velocity difference with the recoils of 6%) are stopped in the slit between the two velocity filters. Detailed adjustments of combinations of the field strengths of the 14 elements have been worked out for the first solution to correct for some of the most common aberrations we are likely to encounter. Monte Carlo-like simulations in the optics code GIOSP have been performed to determine the placement of slits to ensure that no scattered beam reaches the focal plane. These simulations, however, do not take into account the scattering of beam particles off slits or other surfaces, and cannot determine the ratio of scattered beam particles to recoils of interest at the required level, i.e., to 1 part in 10^{12}. One configuration is suitable for operation of the DRS with two focal plane detectors separated by a 2 m drift length for time-of-flight measurements; this setup will aid in particle identification at the focal plane. We are currently investigating the final placement of slits and detectors in the system.

1. University of Liverpool, England.
2. Yale University, New Haven, CT.
3. Tennessee Technological University, Cookeville.
4. University of North Carolina at Chapel Hill, Chapel Hill.
5. A. N. James *et al.*, *Nucl. Instrum. Methods Phys. Res.* A **267**, 144 (1985).
6. M. S. Smith *et al.*, *Nucl. Instrum. Methods Phys. Res.* A **306**, 233 (1991).

ORNL-DWG 96-7939

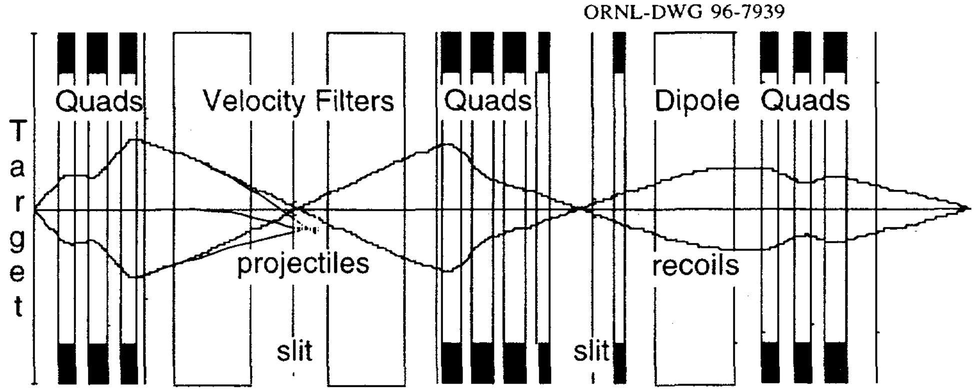

Fig. 1.46. Ion-optical Configuration of the DRS.

THE NATIONAL RIB FACILITY PROJECT

POSSIBLE CONFIGURATION AND LAYOUT FOR A COST-EFFECTIVE HRIBF UPGRADE PROPOSAL

D. K. Olsen, G. D. Alton, J. R. Beene, J. D. Garrett, J. D. Larson,[1] F. Plasil

The Nuclear Science Advisory Committee, NSAC, has recently identified the National Isotope Separator On Line, ISOL, Radioactive Ion Beam, RIB, Facility in its Long Range Plan for U.S. Nuclear Science as the next major facility to be constructed under the auspices of DOE's Nuclear Physics Program Office. A unique opportunity exists for ORNL to be the site chosen for this National ISOL RIB Facility. The configuration of the facility to be proposed by ORNL has, by no means, been determined. Configurations are possible using the present ORIC shielded area with no additional heavy construction, using the present HRIBF complex with the construction of additional heavily shielded space, or constructing the National ISOL Facility, perhaps connected to the National Spallation Neutron Source Project.

One possible very cost-effective configuration, based on using the existing Building 6000 heavily shielded area with only light additional construction, is shown in Fig. 1.47. The new capability with this configuration would be the production of intense neutron-rich fission-fragment radioactive beams. Very intense light-ion beams from a new 200- to 250-MeV proton driver would bombard a high-temperature, thick actinide target located on a new high-voltage RIB injector. Following diffusion from the target, the radioactive atoms would be ionized, mass selected, and, if necessary, charge exchanged before acceleration to ground potential. The existing high-resolution second-stage mass separator would select a single isobar for acceleration in the 25-MV tandem. After acceleration in the tandem, the RIBs, particularly fission fragments, would be boosted to their final energy by a superconducting (SC) linac. Use of the existing 25-MV tandem accelerator, locating the new driver acceleration and target-ion source platform in existing heavily shielded space, and using the existing HV platform system and high-resolution mass separator, make this configuration particularly cost-effective.

Preliminary estimates of the intensities of a variety of interesting RIBs produced with 200 mA of protons stopping in a ^{238}U target have been made. One particularly important beam is ^{132}Sn where a 200-fold intensity increase would result over the HRIBF. The increased intensities relative to those that will be provided by the HRIBF are the result of:

- increased fission yield from the increase in proton energy from 60 to 200-250 MeV;
- increased light-ion beam intensity available from the new driver accelerator; and
- increased transmission through the tandem accelerator resulting from only single stripping.

The construction could be divided into four well-defined elements described below. Some of these elements could be constructed separately, if necessary, to match funding profiles or to minimize the impact on the operation of the existing HRIBF.

Superconducting Linac Booster

An energy booster for the tandem accelerator is required in order to accelerate most fission-fragment RIBs over the Coulomb barrier for nuclear structure studies with single stripping. The design and construction of a superconducting linac booster over the appropriate velocity range is straightforward. Nearly a dozen such boosters have been constructed. The booster would employ independently phased cavities operating at around 100 MHz, with an effective voltage of 40-50 MV and a length of 20-35 m. It will utilize niobium quarter-wave cavities and operate in the $\beta = 0.06$-0.11 range. A new 4000 ft^2 building would be needed to house the booster. The layout shown in Fig. 1.47 allows RIB acceleration through the tandem with or without the booster. In addition, the booster could be brought on line without interrupting operation of the existing HRIBF.

ORIC Replacement

The existing Oak Ridge Isochronous Cyclotron (ORIC), completed in 1961, would be replaced by a new 200- to 250-MeV, 100 to 200-μA proton accelerator. If this accelerator were housed in existing heavily shielded space shown in Fig. 1.47, it would probably need to be a cyclotron. Several cyclotron conceptual design studies have been initiated. The cyclotron could be a compact machine operating at room temperature or at superconducting temperature, a separated-sector machine, or perhaps an H^- machine. A conceptual design for a SC compact cyclotron has been completed by the MSU NSCL based on an existing design for proton therapy. The cyclotron would be installed in room C110 and would be much more reliable and use much less power than ORIC. The main concern with a cyclotron is the septum-induced beam loss at extraction and the resulting machine activation and shielding requirements. More R&D is required in this area. This beam loss would be eliminated with a linac driver, however, a linac would require the construction of new heavily shielded space.

RIB Injector, Mass Separator, and Shielding

In order to have the appropriate tandem injection energy, the target-ion source and first-stage mass separator will be located on high-voltage platforms. Use of existing shielding can be optimized by locating the target ion source in room C109, the present ORIC vault, as shown in Fig. 1.47. Preliminary shielding studies indicate that sufficient local shielding could be added to this configuration to accommodate 200-μA of 235-MeV protons. The remaining space in rooms C109 and C111 will be used to handle highly activated targets. The high-resolution second-stage mass separator will be used in its present location for tandem injection.

Experimental Equipment

The layout shown in Fig. 1.47 is compatible with the utilization of the considerable experimental equipment for nuclear structure and nuclear astrophysics measurements that presently exist at the HRIBF. Additional ancillary equipment and experimental areas would be needed to fully utilize the additional capabilities of the National ISOL Facility.

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1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.

ORNL-DWG 97-5528

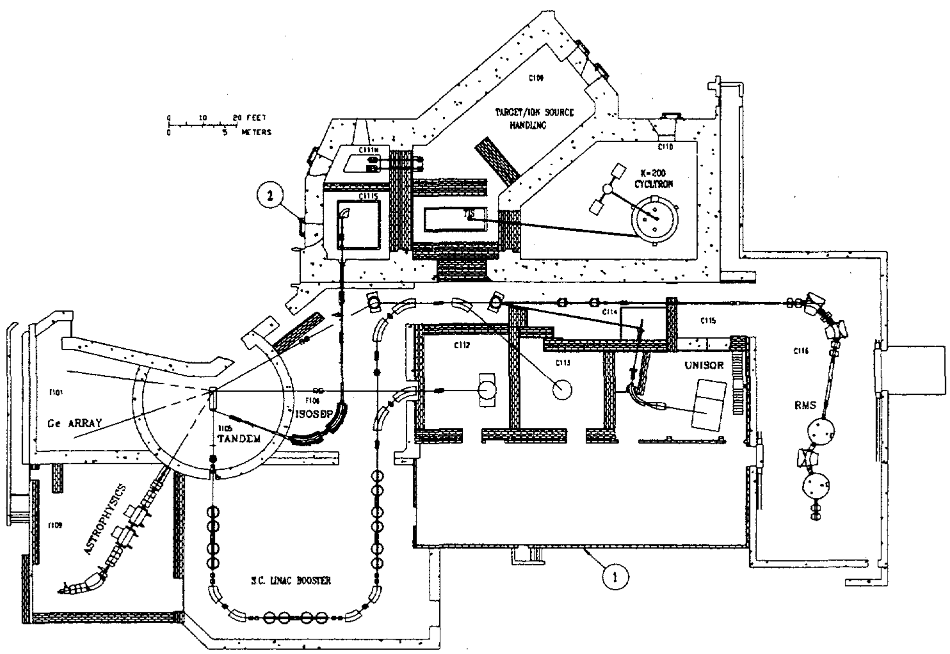

Fig. 1.47

SHIELDING ASSESSMENT FOR THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY UPGRADE

C. O. Slater,[1] D. K. Olsen, J. O. Johnson,[1] R. A. Lillie,[1] T. A. Gabriel[1]

An upgrade to the Holifield Radioactive Ion Beam Facility (HRIBF) is proposed. The upgrade involves increasing the source proton energy and current, resulting in more intense, higher energy radiation to be shielded against. Shielding requirements for the proposed upgrade to the HRIBF have been assessed with respect to weight, space, and dose constraints. Shielding assessments were made for operating, shutdown, and accident conditions. The results indicate reasonable shielding solutions for the RIB-production target room except for the marginal dose rate on the roof. Shielding requirements in the target room were greatly reduced by decisions to move the target to a more interior room and to direct the proton beam downward into the target. A slightly more difficult shielding problem arises for proton beam losses in the cyclotron structure. Here, the assumed isotropic beam losses (hence, neutron emissions) mean higher roof dose rates than those over the target room unless substantial localized shielding is placed over the cyclotron. Shutdown dose rates were found to pose no problems. While dose rates through the sides of the facility during accident conditions will probably satisfy the constraint, dose rates above the roof will be well above the constraints unless a way is devised to shield the locations where beam losses are likely to occur. Ground activation was one of the objectives, but it was not studied.

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1. ORNL Computational Physics and Engineering Division.

SUPERCONDUCTING LINAC BOOSTER FOR THE 25-MV TANDEM ACCELERATOR

D. K. Olsen and J. D. Bailey[1]

The layout and parameters for a superconducting RF linac energy booster for the 25-MV tandem accelerator have been investigated to upgrade the existing HRIBF into the National ISOL Facility. A possible layout for the linac booster is shown in Fig. 1.47 (p.1-69). It was assumed that the major new capability of the upgraded facility would be the production and acceleration of neutron-rich fission-fragment RIBs. These fission fragments would be produced from an actinide target with either a 50 to 60-MeV proton beam from ORIC or a 200 to 250-MeV proton beam from an ORIC replacement accelerator. An important consideration for the linac is the maximum fission-fragment mass to be accelerated. This maximum mass was chosen to be 175 for two reasons: (1) the maximum fission-fragment mass with a useable intensity from 250-MeV proton fission on ^{238}U is around mass 175, and (2) the elements corresponding to masses above 175 tend to be refractory and will not readily release from ^{238}U targets. RIBs with mass 175 can be readily accelerated by the tandem to 2.0 MeV/nucleon operating with a 22-MV terminal potential. With single gas stripping in the tandem terminal, the most optimum charge state is 15+. Consequently, the most important criterion for the linac booster is the capability to accelerate mass-175 ions with a 15+ charge state from 2.0 to 5.5 MeV/nucleon. In addition, all other masses should be accelerated to the highest possible energy, both with and without an additional foil stripping at the linac entrance. The proposed linac is similar in structure to those operating at JAERI, Legnaro, University of Washington, and elsewhere. Simple niobium quarter-wave resonators, with 17-cm inside diameters, will be cooled in sets of four, inside ~ 1.1-m-diameter cylindrical stainless steel cryostats by pot boiling of liquid Helium. Quarter-wave resonators were chosen because of their wide use, mechanical stability, simple construction, and high accelerating field. About 56 resonators, operating at 5.0 MV/m, a synchronous phase angle of 200, and an average transit time factor of 0.95, will be required, assuming 5% of the resonators will not be operable at any given time. Various velocity, or frequency, configurations of these 56 resonators were investigated using exact transit time factors to obtain the highest possible beam energy for masses from 6 to 175 with most probable charge states from single terminal stripping and masses from 40 to 238 for a second stripping at the linac entrance. Although many resonator configurations are more than adequate, including 56 $\beta = 0.100$ 137-Mhz resonators, the most optimum configuration seems to be 28 $\beta = 0.080$ 112-Mhz resonators and 28 $\beta = 0.120$ 168-MHz resonators.

ORNL-DWG 97-5532

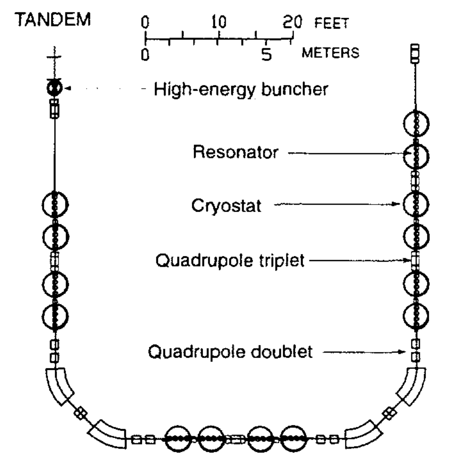

Fig. 1.48

The linac is housed in a building similar to that used in the HISTRAP proposal. The linac consists of three sections separated by 90° achromatic bends. Various radial focusing lattices were investigated to confine the beam radially: FODO cells with the quadrupoles separated by one cryostat and doublets and triplets with the quadrupoles separated by both one and two cryostats. Figure 1.48 shows a triplet configuration, although the other configurations also provide the necessary radial confinement. This layout allows space for a high-energy buncher in room T105, between the slit of BM17 and the shielding wall. Detailed beam dynamic studies have been initiated starting with this configuration in order to understand the longitudinal phase space acceptance of the linac and the bunching requirements. Of particular concern are the bunching requirements and the debunching effects of the 90° achromatic bends.

1. ORNL and the Joint Institute for Heavy Ion Research, Oak Ridge, TN.

INJECTOR SYSTEM CONCEPTS FOR THE NATIONAL RIB FACILITY PROJECT

J. R. Beene, H. Wollnik,[1] D. K. Olsen, G. D. Alton, J. D. Garrett, F. Plasil

As part of the project to develop a proposal for the National RIB Facility, we are working on design concepts for an injector system for the upgraded RIB facility. The basic function of the injector system, as in the present HRIBF, is to prepare a mass and isobar-selected radioactive ion beam for injection, at an energy of about 300 keV, into an accelerator system. The injector system consists of a target and ion source, mass separators, beam transport elements, and, possibly, a charge-exchange cell for production of negative ions. Rather than presenting the details of our current preliminary working design, this write-up is limited to discussing a few underlying design choices that are likely to survive in the final design. The design discussed here was developed assuming the primary driver beam would be approximately 40 kW, with energy in the range 200–250 MeV.

The major departures from the current HRIBF design are related to the provision of a second, separately shielded high-voltage platform (platform zero) on which will be mounted the target and ion source and an additional (zeroth stage) mass separator; the preliminary design is, therefore, a two platform system with three stages of mass separation. The existing platform (platform one) will be reused with significant redesign. The second stage mass separator ($m/\Delta m$ – 20,000) will be reused without modification.

Platform zero will contain the target and ion source, beam focusing elements, and the zeroth stage separator. The primary driver beam is brought vertically down onto the target so that the intense forward neutron yield from the target is directed toward the earth. With the separate target platform, shielding can be placed very near the target and the total mass, therefore, much reduced. The primary beam delivery gantry should be arranged coplanar to the secondary ion beam leaving the source. This allows future flexibility in target and ion source design and size, since the point of interaction of the primary beam with the target can be translated along the secondary beam direction. The current working design incorporates space near the zeroth stage separator to make it possible to introduce additional equipment. This space might be used, for example, to introduce laser beams for very selective laser ion sources. A beam focusing element is needed between the ion source and the zeroth stage separator. In the working design, it is an electrostatic quadrupole quadruplet; care should be taken to ensure that this is a relatively inexpensive device, designed for easy removal and replacement. The zeroth stage mass separator is a modest resolution device ($m/\Delta m \sim 200$) with a deflection angle of ~ 15°. The insulated coupling between platform zero and platform one must be of a large diameter (roughly 10") but with a small diaphragm at the zeroth stage separator side, which allows passage of the selected ion beam, but isolates platform one, as much as possible, from high activity. The current working design calls for two electrostatic quadrupole triplets to be mounted in the coupling region between the two platforms. This arrangement of the focusing elements has a number of advantages, including leaving maximum unfilled space on platform one, but it may pose significant mechanical and electrostatic problems.

Platform one occupies approximately the same space as the current HRIBF platform, but has a significantly different layout. The sector magnet of the HRIBF first stage separator must be replaced with one which matches the geometry of the new system, and achieves roughly the same resolving power ($m/\Delta m \sim 1000$). The charge-exchange cell, if needed, will be placed before the first stage separator, with provisions for adjusting its potential by a few kilovolts relative to platform zero. An electrostatic quadrupole multiplet is positioned between the charge-exchange cell and the separator. Space should also be reserved between the charge-exchange cell and the first stage separator for the possible introduction of as yet undefined beam-cooling devices. From this point on, the changes in the system are small; in particular, the existing second stage mass separator ($m/\Delta m \sim 200{,}000$) is incorporated unchanged into the working design.

1. University of Giessen, Giessen, Germany.

HRIBF USER PROGRAM

HRIBF USER ORGANIZATION

J. D. Garrett and C. J. Gross[1]

The User Organization remained active during the reconfiguration of the Holifield Facility into the first U.S. facility commissioned to accelerate radioactive ions. During this interval information was provided to users on the preparation of the new Radioactive Ion Beam Facility and an effort was made to enlist potential users of the forthcoming radioactive ions. At the present time the user organization is composed of about 338 active members. Users are required to register every three years to insure that they retain their interest in the scientific program of HRIBF. User Group Meetings were held at the Autumn Meetings of Division of Nuclear Physics of the American Physical Society in Williamsburg, VA, in October 1994 and in Bloomington, IN, in October 1995.

A Users Executive Committee is elected each year by the members of the HRIBF Users Organization. The Users Executive Committee for calendar years 1995 and 1996 are given in Tables 1.12 and 1.13 respectively.

The HRIBF Newsletter continues to be distributed about six times a year by email to about 400 members of the User Organization and other interested scientists. Copies of the newsletter and other pertinent information about the HRIBF can be accessed on the World Wide Web at http://www.phy.ornl.gov/. Both the Newsletter and the web information are edited by Carl Gross, the HRIBF Scientific Liaison.

Thirty-four letters of intent to use the HRIBF were received from 99 researchers representing 22 U.S. and 14 foreign institutions in August 1995. These letters of intent were distributed among the categories of astrophysics (6), nuclear reactions (4), and nuclear structure (24).

On August 6, 1996, the Program Advisory Committee (membership given in Table 1.14) met to consider sixteen proposals for 960 hours of research with radioactive ^{69}As and ^{70}As beams and 2008 hours with a variety of stable ion beams. Eight hundred hours of radioactive ion beams and 1000 hours of associated stable ion beams were granted to the ten projects listed in Table 1.15. A dedication of the HRIBF is planned for December 12-13, 1996.

1. Oak Ridge Institute for Science and Education, Oak Ridge, TN.

Table 1.12. HRIBF Users Executive Committee 1995

Carrol Bingham	University of Tennessee
Richard Casten	Brookhaven National Laboratory
Art Champagne (Chairman)	University of North Carolina
Cary Davids	Argonne National Laboratory
Joe Hamilton	Vanderbilt University
Edward Zganjar	Louisiana State University

Table 1.13. HRIBF Users Executive Committee 1996

Carrol Bingham	University of Tennessee
Art Champagne (Chairman)	University of North Carolina
Cary Davids	Argonne National Laboratory
John D'Auria	Simon Frazier University
Joe Hamilton	Vanderbilt University
Mark Riley	Florida State University

Table 1.14. HRIBF PAC 2

Samuel Austin	Michigan State University
James Beene	Oak Ridge National Laboratory
Richard Casten	Brookhaven National Laboratory
Richard Diamond	Lawrence Berkeley Laboratory
William Gelletly	University of Surrey, UK
Wick Haxton	University of Washington
Witek Nazarewicz	University of Tennessee/ORNL
Peter Parker	Yale University

Table 1.15. HRIBF approved experiments

RIB-001	Study of the Doubly-Odd T = 0 Nucleus ^{66}As
RIB-002	Low Energy Coulomb Excitation of ^{69}As and ^{70}As in Inverse Kinematics
RIB-003	Investigation of the Ground State Decays of Nuclei in the Pr-La Mass Region
RIB-004	The Spectroscopy of Very Proton Rich Deformed Nuclei with $Z \approx 60$ & Search for Maximally Deformed Nuclei in the $Z > 50$, $N < 82$ Region
RIB-005	Identification of the Excited States in the $T_z = +1/2$ Nucleus ^{81}Zr
RIB-006	Study of Low-lying Transitions in ^{103}Sn
RIB-007	Identification of Excited States in the Odd-Odd Self-Conjugate Nucleus ^{70}Br
RIB-008	Identification of Light Pr Nuclei
RIB-009	Population Systematics of Light Rare Earth Nuclei
RIB-010	In-beam Spectroscopy of $A \geq 184$ Lead Nuclei with Mass Identification and Recoil Decay Tagging

THE JOINT INSTITUTE FOR HEAVY ION RESEARCH

J. D. Garrett, C. R. Bingham,[1] J. H. Hamilton[2]

The Joint Institute for Heavy Ion Research (JIHIR), administered jointly by the University of Tennessee, Vanderbilt University, and Oak Ridge National Laboratory, has continued its strong support of the HRIBF and its research program. About two-thirds of its funding is derived from the State of Tennessee through the Science Alliance at the University of Tennessee. The remainder is provided by Vanderbilt University, the Department of Energy, and ORNL. The "Joint Institute" is housed in two buildings adjacent to the HRIBF. Its stated purpose is:

> "to promote and support research at the Holifield Facility by providing an intellectual center and physical support for researchers who work at the Holifield."

During the two years covered in this report the Joint has provided full or partial support for the 124 guests listed in Table 1.16. As in previous years, a major portion of the guest support was for nuclear structure and nuclear astrophysics theorists to assist in creating a *milieu* for nuclear structure and radioactive ion beam research at ORNL. The goal is to fill what is perceived as a substantial need in U.S. nuclear science and to complement the experimental program of the HRIBF. One significant accomplishments of this program was attracting Witold Nazarewicz to a theoretical nuclear physics professorship at the University of Tennessee, effective January 1, 1995. This program also has helped to provide "startup" funding for a program at ORNL in theoretical nuclear astrophysics.

During the conversion of the Holifield Facility to a radioactive ion beam facility, the JIHIR also has financed several guests with special technical expertise to assist in the construction of the HRIBF and the associated ancillary experimental equipment for this facility.

The Joint Institute hosted several workshops given in Table 1.17 during fiscal years 1995 and 1996. It also is involved in organizing the HRIBF Dedication December 12-13, 1997.

The Joint Institute also provides lodging accommodations for personnel associated with the scientific program of the Holifield Facility. During fiscal years 1995 and 1996, 113/2917 person/nights of accommodations were utilized.

1. University of Tennessee, Knoxville.
2. Vanderbilt University, Nashville, TN.

Table 1.16. Joint Institute Visitors
October 1, 1994 – September 30, 1996

NAME	INSTITUTION	DATES
ABERG, Sven	Lund Inst. of Technology (Sweden)	10/24/94-11/4/94 6/23/95-8/5/95
ACKLEH, Essam	JIHIR/UT	10/26/94-10/26/95
BAILEY, James	JIHIR/ORNL	7/18/94-Present
BENNETT, John	Univ. of North Carolina	7/31/95-8/3/95
BERGGREN, Tore	Lund Institute of Technology (Sweden)	6/9/95-6/18/95
BEYER, Gerd	Univ. of Geneva (Switzerland)	6/11/96-6/16/96
BHATT, Kumar	Univ. of Mississippi	12/18/94-12/23/94 3/12/95-3/15/95 8/7/95-8/20/95 12/14/95-12/23/95 5/12/96-6/29/96 8/4/96-8/17/96
BLANKENSHIP, James	JIHIR/ORNL	7/1/91-Present
BLOSSER, Henry	Michigan State University	5/9/96-5/10/96
BLUME, Christoph	Univ. of Muenster	3/12/96-4/10/96
BRAGE, Tomas	NASA/Goddard Space Flight Center	4/22/96-4/24/96
CASTEN, Rick	Brookhaven National Lab.	2/2/95-2/3/95
CHAMPAGNE, Arthur	Univ. of North Carolina at Chapel Hill	2/15/96-2/18/96
CHATTERJEE, Lali	JIHIR/UT	7/1/96-Present
CHAVEZ-LOMELI, Efrain	Univ. Nac. Autonoma de Mexico (IFUNAM)	10/25/94-11/8/94 7/17/95-8/4/95 7/15/96-8/4/96
CHEN, Xue-Shi	Inst. of Nuclear Res. (China)	1/25/95-11/30/95
CHEN, Yong Shou	China Inst. of Atomic Energy (China)	11/2/95-11/22/95
COLGATE, Sterling	Los Alamos National Lab.	7/31/96-8/2/96
CUI, Baoqun	China Institute of Atomic Energy	2/28/96-Present
CWIOK, Stefan	Warsaw Univ. (Poland)	7/2/95-8/16/95 9/16/96-10/17/96
DANIELS, Andrei	Joint Inst. for Nuclear Research, Dubna (Russia)	12/13-16/94
DAS, Jiban	Nuclear Science Centre (India)	12/1/94-11/16/95
DAVINSON, Thomas	Univ. of Edinburgh (United Kingdom)	6/12/96-6/19/96 8/3/96-8/12/96
DEAN, David	California Inst. of Tech.	10/1/94-10/6/94
DELLWO, Joe	JIHIR/ORNL	9/1/92-1/13/95

Table 1.16. Joint Institute Visitors (continued)

NAME	INSTITUTION	DATES
DI BARTOLO, Gaetano	Inst. Nazionale Di Fisica Nucleare, Catania (Italy)	4/9/94-4/8/95 5/30/95-6/19/95
DICKENS, Justin	JIHIR/ORNL	1/1/96-Present
DOBACZEWSKI, Jacek	Warsaw Univ (Poland)	10/1/94-12/20/94 6/30/95-7/30/95 8/4/96-8/31/96
DôNAU, Friedrich	Research Center Rossendorf, Inc. (Germany)	8/30/96-9/27/96
DU, Hong	Univ. of Connecticut	1/14/96-1/20/96
EKSTROM, Peter	Lund Univ. (Sweden)	2/7/96-2/10/96
ENGEL, Johnathan	Univ. of North Carolina	7/31/95-8/3/95
FENG, Da Hsuan	Drexel Univ.	10/10/94-10/17/94 2/1/96-2/4/96
FRYXELL, Bruce	NASA/Goddard Space Flight Center	2/1/96-2/4/96
GELLETLY, William	Univ. of Surrey (United Kingdom)	7/31/96-8/7/96
GREINER, Martin	Justus Liebig Univ. (Germany)	9/19/94-10/17/94 10/1/95-10/4/95
GREINER, Walter	Inst. fur Theoretische Physik (Germany)	1/15/95-1/24/95 2/22/95-2/24/95 3/1/95-3/2/95 9/28/95-9/30/95 1/21/96-2/3/96 2/24/96-2/25/96 2/28/96 4/26/96-4/28/96 7/18/96-8/2/96
GUBER, Klaus	JIHIR/ORNL	7/26/94-Present
GUPTA, Mohini	Univ. of Bombay (India)	12/2/94-4/30/95 6/14/96-Present
HAAS, Bernard	C.N.R.S., Strasbourg (France)	12/5/95-12/19/94
HACKMANN, Gregg	McMaster Univ. (Canada)	12/12/94-12/13/94
HALBERT, Melvyn	JIHIR/ORNL	1/1/95-Present
HAN, Xiao-Ling	Chung Yuan Christian Univ. (China)	7/12/95-9/10/95 6/7/96-6/18/96
HARVEY, Jack	JIHIR/ORNL	5/1/95-Present
HEENEN, Paul-Henri	Univ. of Libre de Bruxelles (Belgium)	8/4/96-8/18/96
HEYDE, Kris	Univ. of Gent (Belgium)	5/19/96-6/5/96
HIRSCH, Jorge	CINVESTAV (Mexico)	8/11/96-8/17/96
HOREN, Daniel	JIHIR/ORNL	1/1/95-6/30/95 12/19/95-12/20/95 1/1/96-12/31/96 3/4/96-3/9/96 4/15/96
HOWELL, Calvin	Duke Univ.	2/2/95-2/3/95

Table 1.16. Joint Institute Visitors (continued)

NAME	INSTITUTION	DATES
HUANG, Jian	Drexel Univ.	12/12/94-12/18/94 2/27/95-3/6/95 6/3/96-6/5/96
HUO, Junde	Jilin Univ. (China)	5/26/95-9/2/95
JAMES, Arthur	Univ. of Liverpool (United Kingdom)	7/23/96-8/7/96
JOHNSON, Noah	JIHIR/ORNL	1/1/95-Present
JONES, Charles	JIHIR/ORNL	1/1/96-Present
JOSHI, Paresh	JIHIR/ORNL	2/1/95-5/10/95
KAHANE, Sylvian	Nuclear Research Center-Negev (Israel)	7/9/95-8/21/96
KANEKO, Kaznunari	Kyushu Sangyo Univ. (Japan)	9/1/96-Present
KAMYSHKOV, Yuri	JIHIR/UT	7/1/96-Present
KANGASMAKI, Aki	Univ. of Helsinki (Finland)	2/27/96-3/12/96
KEINONEN, Juhani	Univ. of Helsinki (Finland)	7/27/95-8/11/95 6/25/96-7/12/96
KIM, Hee	JIHIR/ORNL	10/1/94-5/31/96
LAMOREAUX, Steve	Univ. of Washington	8/29/95-9/3/95
LAURITSEN, Torben	Argonne National Lab.	2/5/96-2/11/96
LOEBNER, Kurt	Ludwig-Maximilians Univ. (Germany)	9/4/96-10/1/96
LOHWASSER, Reinhard	Ludwig-Maximilians Univ. (Germany)	9/18/95-11/24/95 5/30/96-Present
MARUHN, Joachim	Univ. of Frankfurt (Germany)	9/25/94-10/16/94 9/29/95-10/3/95 4/2/96-4/8/96
MACKENZIE, John	Univ. of Edinburgh (United Kingdom)	6/12/96-6/19/96 8/3/96-8/12/96
MCGOWAN, Francis	JIHIR/ORNL	11/17/90-11/30/95
MEZZACAPPA, Anthony	JIHIR/ORNL	12/1/94-Present
MIDDLETON, Jerry	Mississippi State Univ.	7/16/95-7/22/95 12/20/95-Present
MIZUTORI, Shjiro	Lund Institute of Technology (Sweden)	1/4/96-Present
MUELLER, Paul	JIHIR/ORNL	9/1/91-3/31/95
NAZAREWICZ, Witold	JIHIR/UT	1/7/91-12/31/94
NESTOR, Charles	JIHIR/ORNL	1/1/95-Present
NINOV, Victor	Technische Hochschule (Germany)	1/14/96-1/20/96
OBERACKER, Volker	Vanderbilt Univ.	7/20/95-8/19/95 7/19/96-8/19/96
OLIVE, Don	Campbellsville College	5/10/95-8/11/95 7/18/96-8/31/96 9/1/96-Present
ORMAND, Erich	JIHIR/UT	10/1/94-12/31/95

Table 1.16. Joint Institute Visitors (continued)

NAME	INSTITUTION	DATES
PAPP, Tabor	Inst. of Nuclear Res. of the Hungarian Academy of Sciences (Hungary)	7/1/96-7/5/96
PETROVICI, Alexandrina	Central Inst. of Physics (Romania)	10/10/95-10/13/95
PIEKSMA, Marc	Univ. Catholique de Louvain (Belgium)	7/1/96-7/24/96
PIERCEY, Rodney	Mississippi State Univ.	10/1/95-5/31/96
PIOTROWSKI, Antoni	Soltan Inst. for Nuclear Res. (Poland)	4/3/95-9/1/95
RAB, Shaheen	Kuwait Inst. for Scientific Research	6/1/92-3/31/95
RADFORD, David	Chalk River Laboratories (Canada)	2/7/96-2/10/96
RATYNSKI, Wojciech	Soltan Inst. for Nuclear Studies (Poland)	11/5/95-11/15/95
RAVN, Helge	CERN (Switzerland)	10/17/94-10/29/94 3/3/96-3/16/96
RISCHKE, Dirk	Columbia Univ.	11/28/95-11/30/95
ROHOZINSKI, Stanislaw	Warsaw University (Poland)	1/10/95-2/2/95
ROWLEY, Neil	Univ. of Manchester (United Kingdom)	7/3/95-7/9/95
RYKACZEWSKI, Krzysztof	Warsaw Univ. (Poland)	6/23/95-6/29/95 1/30/96-2/4/96
SAINI, Surender	JIHIR/ORNL	7/24/88-12/31/94
SALOVAARA, Kim	Royal Inst. of Technology, Stockholm (Sweden)	3/12/96-9/7/96
SANDULESCU, Aureliu-Emil	Romanian Academy	10/31/94-11/3/94
SATULA, Wojciech	Univ. of Warsaw (Poland)	11/8/95-11/11/95 2/1/96-Present
SAVARD, Guy	Chalk River Laboratories (AECL)	6/15/96-6/29/96
SCHLAGHECK, Hubertus	Univ. of Muenster (Germany)	3/12/96-4/10/96
SCHMORAK, Marcel	JIHIR/ORNL	11/1/91-9/30/95
SCHUESSLER, Hans	Texas A&M Univ.	6/9/96-6/13/96 7/24/96-7/29/96
SHEIKH, Javid	TATA Institute of Fundamental Research, Bombay (India)	6/5/96-7/21/96
STEIN, Ekkehart	Univ. of Frankfurt (Germany)	2/18/96-3/3/96
STRACENER, Daniel	JIHIR/ORNL	6/3/96-Present
SOUSA, David	Eastern Kentucky Univ.	5/22/95-6/16/95 5/20/96-6/10/96
SUN, Yang	JIHIR/ORNL	10/10/94-10/17/94 12/28/94-Present

Table 1.16. Joint Institute Visitors (continued)

NAME	INSTITUTION	DATES
SUNDELL, Stig	CERN (Switzerland)	9/29/94-11/9/94 3/23/95-4/22/95 9/30/95-11/5/95
SZERYPO, Jerzy	Inst. of Experimental	2/13/96-2/18/96
TALBERT, Willard	Amparo Corp. (New Mexico)	1/23/95-1/27/95 2/27/95-3/3/95 3/27/95-3/31/95 6/1/95-12/1/95
THIELEMANN, Friedrich	Univ. of Basel (Switzerland)	7/9/96-7/19/96
THOENNESSEN, Michael	Michigan State Univ.	6/1/95-6/3/95
TIAN, Wei	China Inst. of Atomic Energy	4/27/96-10/27/96
TIKKANEN, Pertti	Univ. of Helsinki (Finland)	7/26/95-8/9/95
VALLIERES, Michel	Drexel Univ.	10/18/94-10/23/94 2/1/96-2/4/96
VERGADOS, John	Univ. of Ioannina (Greece)	8/14/96-8/17/96
VIDOVIC, Mario	Johann Wolfgang, Goethe Univ. (Germany)	8/29/94-11/30/94
WERNER, Tomek	Inst. of Theoretical Physics (Poland)	4/12/93-9/30/95
WHITE, Jody	California Institute of Technology	1/22/96-4/22/96
WOLLNIK, Hermann	Univ. of Giessen (Germany)	3/3/95-4/13/95 7/25/95-8/18/95 3/18/96-3/31/96 8/13/96-8/21/96
WOODS, Philip	Univ. of Edinburgh (United Kingdom)	8/3/96-8/12/96
WU, Cheng-Li	Chung Yuan Christian Univ. (China)	7/12/95-9/10/95 7/7/96-7/18/96
WYSS, Ramon	Royal Inst. of Tech., Stockholm (Sweden)	8/12/96-8/30/96
XU, Feng	Drexel Univ.	6/3/96-6/5/96
ZELDES, Nissan	Hebrew Univ. (Israel)	7/22/94-2/22/95
ZHANG, Tian	Inst. of Applied Physics & Computational Mathematics (China)	1/12/95-4/29/95
ZHU, Yaoyin	Carnegie Mellon Univ.	7/15/94-10/31/94

Table 1.17. Meetings sponsored by the Joint Institute for Heavy Ion Research

MEETING	DATE	ATTENDEES	ORGANIZER
Discussions on Detectors for the Focal Plan of the RMS	12/1-3/94	35	C. J. Gross
HRIBF Users Workshop	6/2-3/95	110	C. J. Gross
Data Analysis Workshop	2/7-10/96	70	H.-Q. Jin, W. Reviol
UNIRIB Meeting	6/10-11/96	40	L. Riedinger
Vanderbilt Summer Science Collaborative	6/19-21/96	30	J. Hamilton

ABSTRACTS OF PAPERS PUBLISHED OR SUBMITTED FOR PUBLICATION

AN INTERNAL TIMING PROBE FOR USE IN THE MSU K1200 CYCLOTRON[1]

J. D. Bailey,[2] J. Kuchar,[3] F. Marti,[3] J. Ottarson[3]

A probe was installed in the K1200 to measure the internal beam time structure as a function of radius. Using the fast rise times of a Si detector, which was specially cut to extend the active area to within 150 μm of the detector edge, the time of arrival of the heavy ions on the detector is measured with respect to the accelerating RF voltage. Limited to count rates of several kHz, use of the detector requires attenuation of the injected beam, and permits studies of single particle beam dynamics.

1. Abstract of published paper: *Proceedings of the 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995*, p. 369.
2. The Joint Institute for Heavy Ion Research has as member institutions the University of Tennessee, Vanderbilt University, and the Oak Ridge National Laboratory; it is supported by the members and by the Department of Energy through Contract Number DE-FG05-87ER40361 with the University of Tennessee.
3. Work supported by U.S. National Science Foundation grant PHY-9214992 at the National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI.

AXIAL INJECTION AND PHASE SELECTION STUDIES OF THE MSU K1200 CYCLOTRON[1]

J. D. Bailey[2]

Axial injection into a cyclotron through its iron yoke, a spiral inflector, and the central region electrodes couples the transverse coordinates of motion together, as well as with the longitudinal coordinates. The phase slits in the K1200 cyclotron use the r-j correlations inherent in acceleration of ions in a cyclotron. Computer simulations of injection into and acceleration within the K1200 cyclotron encompassing the four transverse dimensions together with time were used to determine beam matching requirements for injection and phase selection in the K1200 cyclotron. The simulations were compared with measurements using an internal timing probe.

1. Abstract of published paper: *Procceedings of the 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995*, p. 372.
2. The Joint Institute for Heavy Ion Research has as member institutions the University of Tennessee, Vanderbilt University, and the Oak Ridge National Laboratory; it is supported by the members and by the Department of Energy through Contract Number DE-FG05-87ER40361 with the University of Tennessee.

ORIC CENTRAL REGION CALCULATIONS[1]

J. D. Bailey,[2] D. T. Dowling, S. N. Lane, S. W. Mosko, D. K. Olsen, B. A. Tatum

The central region for the K = 100 Oak Ridge Isochronous Cyclotron, ORIC, will be modified to provide better orbit centering, focusing of orbits in the axial direction, and phase selection, in order to improve extraction efficiency, and reduce radioactive activation of cyclotron parts. The central region is specifically designed for the acceleration of intense light ion beams such as 60 MeV protons and 15 - 100

MeV alphas. These beams will be used in the production of radioactive particles in the Radioactive Ion Beam Project at Oak Ridge National Laboratory.

1. Abstract of published paper: *Proceedings of 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995*, p. 366.
2. The Joint Institute for Heavy Ion Research has as member institutions the University of Tennessee, Vanderbilt University, and the Oak Ridge National Laboratory; it is supported by the members and by the Department of Energy through Contract Number DE-FG05-87ER40361 with the University of Tennessee.

STATUS OF THE RADIOACTIVE ION BEAM INJECTOR AT THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

D. T. Dowling, R. L. Auble, M. R. Dinehart, D. L. Haynes, J. W. Johnson,[2] R. C. Juras, Y. S. Kwon,[3] M. J. Meigs, G. D. Mills, S. W. Mosko, D. K. Olsen, B. A. Tatum, C. L. Williams,[4] H. Wollnik[5]

The Holifield Radioactive Ion Beam Facility (HRIBF) is a first generation radioactive ion beam (RIB) facility. Project construction commenced in FY93 with the initial emphasis placed on conversion of a heavily shielded room from an experiment area to an area suitable for housing the RIB injector. The RIB injector is the central component of the RIB project. The injector consists of two electrically connected high voltage platforms which are designed to operate at -300 kilovolts and which are separated by a shield wall. One platform houses controls, instrumentation, and power supplies. The second platform is the location of an ISOLDE type target/ion source which will be bombarded with intense light ion beams from the ORIC. Additionally, this platform houses the first stage mass separation system which is designed for 1 part in 2000 mass resolution, electrostatic quadrupole lenses/steerers for beam transport, and a cesium charge exchange cell for conversion of positive ions to negative ions for injection into the tandem accelerator. This paper details the design, installation and commissioning aspects of the injector development.

1. Abstract of published paper: *Proceedings of the 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995*, p. 1897.
2. Consultant.
3. ORNL Plant and Equipment Division.
4. Consultant, Gilbert/Commonwealth.
5. University of Giessen, Germany.

A NEW BEAM INTENSITY MONITORING SYSTEM WITH SIDE DYNAMIC RANGE FOR THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

M. J. Meigs, D. L. Haynes, C. M. Jones, C. T. LeCroy

A new beam intensity monitoring system with a wide dynamic range has been designed, fabricated and tested for use at the Holifield Radioactive Ion Beam Facility (HRIBF). Radioactive ion beams produced with this first generation facility will have intensities much lower than those of stable ions previously injected into the 25URC tandem accelerator and the existing beam current monitoring systems, which have a lower limit of approximately 100 pA, will not be adequate to tune the injection line or accelerator. This paper describes a new system which combines a Faraday cup and a continuous dynode electron multiplier (CDEM) to yield a dynamic range from a few particles per second to greater than a microampere. The CDEM can be biased to count either secondary electrons or Rutherford backscattered ions.

1. Abstract of published paper: *Proceedings of the 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995*, p. 2643.

DEVELOPMENT OF THE HRIBF 25-MV TANDEM ACCELERATOR AS A RIB ACCELERATOR[1]

M. J. Meigs, D. L. Haynes, C. M. Jones, R. C. Juras

The Holifield Facility 25URC Tandem Accelerator will begin accelerating radioactive ion beams (RIBs) for nuclear structure and astrophysics research in 1995. This paper addresses the development of the accelerator to allow optimum operation with the particular challenges of transmitting RIBs. New diagnostics for ultra-low intensity beams are being installed and the terminal potential stabilization system is being studied to optimize control with these low currents. The new resistor-based voltage-grading-system has aided more stable operation as well as allowing operation at very low terminal potentials which is required for some astrophysics experiments. Radiation safety issues for the accelerator are being met with administrative control as well as possible modifications which could include some shielding in vulnerable areas. Also addressed is beam transmission optimization, particularly at low terminal potentials, and new high terminal potential records expected in 1995.

1. Abstract of published paper: Proceedings of International Conference on Heavy Ion Accelerator Technology, Canberra, Australia, Sept. 18-22, 1995, *Nucl. Instrum. Methods Phys. Res. A* **382**, 51 (1996).

THE 25URC TANDEM RESISTOR-BASED VOLTAGE GRADING SYSTEM: INSTALLATION AND FIRST OPERATING EXPERIENCE[1]

M. J. Meigs, C. M. Jones, R. C. Juras, D. L. Haynes

On June 27, 1994, installation work was completed on a new resistor-based voltage grading system for the Holifield facility tandem accelerator. After installation, the accelerator was easily conditioned to 20.7 MV and then used for development studies with no apparent problems. This paper describes the installation and first operating experience with the new grading system.

1. Abstract of paper submitted to the Symposium of Northeastern Accelerator Personnel, Kalamazoo, Michigan, October 12-15, 1994.

FIRST GENERATION ISOL RADIOACTIVE ION BEAM FACILITIES[1]

D. K. Olsen

Widespread scientific interest has developed in using accelerated Radioactive Ion Beams (RIBs) for nuclear physics, astrophysics, solid-state physics, and applied studies. Two general methods can be used to produce RIBs: the recoil fragmentation method and the Isotope-Separator-On-Line (ISOL) method. The recoil-fragmentation method requires one accelerator, filters radioactive fragments produced from medium-energy heavy-ion beams incident on thin targets, and is relatively well developed. This method has been pursued vigorously at several laboratories. The ISOL method requires two accelerators, has the promise of lower energies and more intense beams, and is in an earlier state of development. The status, challenges, and plans of the first-generation ISOL accelerated RIB facilities presently operating or under construction will be discussed. These are facilities based in part on at least one existing accelerator and will produce limited RIB beam species, intensities, and energies.

1. Abstract of published paper: *Proceedings of the 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995*, p. 312.

PROGRESS, STATUS, AND PLANS FOR THE HRIBF PROJECT[1]

D. K. Olsen, R. L. Auble, G. D. Alton, J. D. Bailey,[2] M. R. Dinehart, C. L. Dukes, D. T. Dowling, D. L. Haynes, C. M. Jones, S. N. Lane, C. T. LeCroy, R. C. Juras, M. J. Meigs, G. D. Mills, S. W. Mosko, P. E. Mueller, S. N. Murray, B. A. Tatum, R. F. Welton,[3] H. Wollnik[4]

Othe last three years, the Holifield accelerator system has been reconfigured into a first-generation radioactive ion beam facility, the HRIBF, a national user facility for RIB research. The construction and reconfiguration have been completed and the equipment commissioning and beam development phases have started. The progress to date, the present status, and future plans will be given. The special problems connected with the production and acceleration of RIBs will be discussed.

1. Abstract of published paper: Proceedings of International Conference on Heavy Ion Accelerator Technology, Canberra, Australia, Sept. 18-22, 1995, *Nucl. Instrum. Methods Phys. Res. A* **382**, 197 (1996).
2. ORNL and the Joint Institute for Heavy Ion Research, which has as member institutions the University of Tennessee, Vanderbilt University, and the Oak Ridge National Laboratory; it is supported by the members and by the Department of Energy through Contract Number DE-FG05-87ER40361 with the University of Tennessee.
3. Oak Ridge Associated Universities, Oak Ridge, TN, and Georgia Institute of Technology, Atlanta.
4. University of Giessen, Germany.

CONTROL SYSTEM FOR THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

B. A. Tatum, R. C. Juras, M. J. Meigs

A new accelerator control system is being implemented as part of the development of the Holifield Radioactive Ion Beam Facility (HRIBF), a first generation radioactive ion beam (RIB) facility. The pre-existing accelerator control systems are based on 1970's technology and addition or alteration of controls is cumbersome and costly. A new, unified control system for the cyclotron and tandem accelerators, the RIB injector, ion sources, and accelerator beam lines is based on a commercial product from Vista Control Systems, Inc. Several other accelerator facilities, as well as numerous industrial sites, are now using this system. The control system is distributed over a number of computers which communicate over Ethernet and is easily extensible. Presently, the HRIBF implementation is based on VAX/VMS, VAX/ELN, VME, and Allen-Bradley PLC5 programmable logic controller architectures. Expansion to include UNIX platforms and CAMAC hardware support is planned. Operator interface is via X-terminals. The system has proven to be quite powerful, yet it has been easy to implement with a small staff. A Vista users group has resulted in shared software to implement specific controls. This paper describes system features and the present and future implementations at the HRIBF in detail.

1. Abstract of published paper: *Proceedings of the 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995*, p. 2202.

A POSITIVE (NEGATIVE) SURFACE IONIZATION SOURCE CONCEPT FOR RADIOACTIVE ION BEAM GENERATION[1]

G. D. Alton and G. D. Mills

A novel, versatile, new concept, spherical-geometry, positive (negative) surface-ionization source has been designed and fabricated which will have the capability of generating both positive- and negative-ion beams without mechanical changes to the source. The source utilizes a highly permeable, high-work-function Ir ionizer (f ≅ 5.29 eV) for ionizing highly electropositive atoms/molecules; while for negative-surface ionization, the work function is lowered to f ≅ 1.43 eV by continually feeding cesium vapor through the ionizer matrix. The use of Cs to effect low work function surfaces for negative ion beam generation has the potential of overcoming the chronic poisoning effects experienced with LaB_6 while enhancing the probability for negative ion formation of atomic and molecular species with low to intermediate electron affinities. The flexibility of operation in either mode makes it especially attractive for radioactive ion beam (RIB) applications and, therefore, the source will be used as a complementary replacement for the high-temperature electron impact ionization sources presently in use at the Holifield Radioactive Ion Beam Facility (HRIBF). The design features and operational principles of the source will be described in this report.

1. Abstract of published paper: Proceedings of International Conference on Heavy Ion Accelerator Technology, Canberra, Australia, Sept. 18-22, 1995, *Nucl. Instrum. Methods Phys. Res. A* **382**, 232 (1996).

A NEW CONCEPT TANDEM THERMAL DISSOCIATOR/ELECTRON IMPACT ION SOURCE FOR RIB GENERATION[1]

G. D. Alton and C. Williams

An innovative thermal dissociation/electron impact ionization positive ion source is presently under design at the Oak Ridge National Laboratory for potential use for generating RIBs at the Holifield Radioactive Ion Beam Facility (HRIBF). Because of the low probability of simultaneously dissociating and efficiently ionizing the individual atomic constituents with conventional, hot-cathode, electron-impact ion sources, the ion beams extracted from these sources often appear as a mixture of several molecular sideband beams. In this way, the intensity of the species of interest is diluted. We have conceived an ion source that combines the excellent molecular dissociation properties of a thermal dissociator and the high efficiency characteristics of an electron impact ionization source. If the concept proves to be a viable option, the source will be used as a complement to the electron beam plasma ion sources already in use at the HRIBF. The design features and principles of operation of the source are described in this article.

1. Abstract of published paper: Proceedings of International Conference on Heavy Ion Accelerator Technology, Canberra, Australia, Sept. 18-22, 1995, *Nucl. Instrum. Methods Phys. Res. A* **382**, 237 (1996).

TARGETS AND ION SOURCES FOR RIB GENERATION AT THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

G. D. Alton

The Holifield Radioactive Ion Beam Facility (HRIBF), now under construction at the Oak Ridge National Laboratory, is based on the use of the well-known on-line isotope separator (ISOL) technique in which radioactive nuclei are produced by fusion type reactions in selectively chosen target materials by high-energy proton, deuteron, or He ion beams from the Oak Ridge Isochronous Cyclotron (ORIC). Among several major challenges posed by generating and accelerating adequate intensities of radioactive ion beams (RIBs), selection of the most appropriate target material for production of the species of interest is, perhaps, the most difficult. In this report, we briefly review present efforts to select target materials and to design composite target matrix/heat-sink systems that simultaneously incorporate the short diffusion lengths, high permeabilities, and controllable temperatures required to effect maximum diffusion release rates of the short-lived species that can be realized at the temperature limits of specific target materials. We also describe the performance characteristics for a selected number of target ion sources that will be employed for initial use at the HRIBF as well as prototype ion sources that show promise for future use for RIB applications.

1. Abstract of published paper: Proceedings of International Conference on Heavy Ion Accelerator Technology, Canberra, Australia, Sept. 18-22, 1995, *Nucl. Instrum. Methods Phys. Res. A* **382**, 207 (1996).

SELECTION OF RIB TARGETS USING ION IMPLANTATION AT THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

G. D. Alton and J. Dellwo

Among several major challenges posed by generating and accelerating adequate intensities of RIBs, selection of the most appropriate target material is perhaps the most difficult because of the requisite fast and selective thermal release of minute amounts of the short-lived product atoms from the ISOL target in the presence of bulk amounts of target material. Experimental studies are under way at the Oak Ridge National Laboratory (ORNL) which are designed to measure the time evolution of implanted elements diffused from refractory target materials which are candidates for forming radioactive ion beams (RIBs) at the Holifield Radioactive Ion Beam Facility (HRIBF). The diffusion coefficients are derived by comparing experimental data with numerical solutions to a one-dimensional form of Fick's second law for ion implanted distributions. In this report, we describe the experimental arrangement, experimental procedures, and provide time release data and diffusion coefficients for releasing ion implanted ^{37}Cl from Zr_5Si_3 and ^{75}As, ^{79}Br, and ^{78}Se from Zr_5Ge_3 and estimates of the diffusion coefficients for ^{35}Cl, ^{63}Cu, ^{65}Cu, ^{69}Ga and ^{71}Ga diffused from BN; ^{35}Cl, ^{63}Cu, ^{65}Cu, ^{69}Ga, ^{75}As, and ^{78}Se diffused from C; ^{35}Cl, ^{68}Cu, ^{69}Ga, ^{75}As, and ^{78}Se diffused from Ta.

1. Abstract of published paper: Proceedings of International Conference on Heavy Ion Accelerator Technology, Canberra, Australia, Sept. 18-22, 1995, *Nucl. Instrum. Methods Phys. Res. A* **382**, 225 (1996).

BROADBAND FREQUENCY ECR ION SOURCE CONCEPTS WITH LARGE RESONANT PLASMA VOLUMES[1]

G. D. Alton

New techniques are proposed for enhancing the performances of ECR ion sources. The techniques are based on the use of high-power, variable-frequency, multiple-discrete-frequency, or broadband microwave radiation, derived from standard TWT technology, to effect large resonant "volume" ECR sources. The creation of a large ECR plasma "volume" permits coupling of more power into the plasma, resulting in the heating of a much larger electron population to higher energies, the effect of which is to produce higher charge state distributions and much higher intensities within a particular charge state than possible in present forms of the ECR ion source. If successful, these developments could significantly impact future accelerator designs and accelerator-based, heavy-ion-research programs by providing multiply-charged ion beams with the energies and intensities required for nuclear physics research from existing ECR ion sources. The methods described in this article can be used to retrofit any ECR ion source predicated on B-minimum plasma confinement techniques.

1. Abstract of published paper: Proceedings of International Conference on Heavy Ion Accelerator Technology, Canberra, Australia, Sept. 18-22, 1995, *Nucl. Instrum. Methods Phys. Res. A* **382**, 276 (1996).

SOURCES OF LOW-CHARGE-STATE POSITIVE-ION BEAMS[1]

G. D. Alton

Ion beams are used pervasively in many areas of fundamental and applied research and for a growing number of industrial applications, thus emphasizing the importance of the ion source to modern science and technology. Ion source development has been, historically, driven by the needs of the basic and applied research communities and, in more recent years, by the needs of the industrial communities for sources with improved performance attributes, including operational reliability, life-time, beam quality (emmitance), and intensity, for a growing number of applications. These applications include basic and applied research, isotope separation, mass spectroscopy, fusion energy, inertial confinement, and radiation therapy, as well as a growing and diverse number of industrial applications such as ion beam lithography, semiconducting material doping, ion beam deposition, modification of material surfaces, (e.g., conductibility, wear, and corrosive resistance), and probe beams for the important analytical fields of secondary ion mass spectrometry (SIMS), accelerator mass spectrometry (AMS), Rutherford backscattering spectroscopy (RBS), proton-induced X-ray excitation (PIXE), nuclear reaction analysis (NRA), and elastic recoil detection analysis (ERDA). All of these applications are dependent on the use of ion beams and, consequently, on the technologies for their production. Such sources of ions constitute an important set of technologies, each of which may vary widely in complexity, depending on the method required to produce the desired ion species and beam intensity.

1. Abstract of published paper: *Atomic, Molecular, and Optical Physics: Charged Particles* **29A**, pp. 69 ff. (1995).

FUTURE PROSPECTS FOR ECR ION SOURCES WITH IMPROVED CHARGE STATE DISTRIBUTIONS[1]

G. D. Alton

Despite the steady advance in the technology of the ECR ion source, present art forms have not yet reached their full potential in terms of charge state and intensity within a particular charge state, in part, because of the narrow band width, single-frequency microwave radiation used to heat the plasma electrons. This article identifies fundamentally important methods which may enhance the performances of ECR ion sources through the use of: 1) a tailored magnetic field configuration (spatial domain) in combination with single-frequency microwave radiation to create a large uniformly distributed ECR "volume" or 2) the use of broadband frequency domain techniques (variable-frequency, broad-band frequency, or multiple-discrete-frequency microwave radiation), derived from standard TWT technology, to transform the resonant plasma "surfaces" of traditional ECR ion sources into resonant plasma "volumes". The creation of a large ECR plasma "volume" permits coupling of more power into the plasma, resulting in the heating of a much larger electron population to higher energies, thereby producing higher charge state ions and much higher intensities within a particular charge state than possible in present forms of the source. The ECR ion source concepts described in this article offer exciting opportunities to significantly advance the-state-of-the-art of ECR technology and as a consequence, open new opportunities in fundamental and applied research and for a variety of industrial applications.

1. Abstract of published paper: *Proceedings of the 14th International Conference on Cyclotrons and Their Applications,* Cape Town, S. Africa, World Scientific Publishing Co., Ed. J. C Cornell, p. 362 ff. (1995).

STATUS REPORT FOR THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

D. K. Olsen, R. L. Auble, G. D. Alton, D. T. Dowling, D. L. Haynes, S. N. Lane, R. C Juras, M. J. Meigs, G. D. Mills, S. W. Mosko, P. E. Mueller, B. A. Tatum, J. D. Bailey,[2] C. M. Jones, R. F. Welton,[3] H. Wollnik[4]

In 1992, the HHIRF became a project to develop a first-generation radioactive ion beam facility, the HRIBF, a national user facility for RIB research. Intense beams from ORIC will produce radioactive atoms as reaction products in thick targets using an ISOL-type target-ion source mounted on a 300-kV RIB injector. These radioactive atoms will be ionized, mass analyzed, charge exchanged, accelerated to ground potential, and analyzed again to separate isobars with a second-stage mass analyzer. The resulting RIBs will be injected into the randem and accelerated to energies of interest for nuclear physics and astrophysics studies. The construction phase of the project has been completed. A report on the status and progress developing the the facility is given, along with the long term development plans.

1. Abstract of published paper: *Proceedings of the 14th International Conference on Cyclotrons and Their Applications,* Cape Town, S. Africa, World Scientific Publishing Co., Ed. J. C Cornell, p. 634 ff. (1995).

A COMBINED THERMAL DISSOCIATION AND ELECTRON IMPACT IONIZATION SOURCE FOR RADIOACTIVE ION BEAM GENERATION[1]

G. D. Alton and C. Williams[2]

The probability for simultaneously dissociating and efficiently ionizing the individual atomic constituents of molecular feed materials with conventional, hot-cathode, electron-impact ion sources is low and consequently, the ion beams from these sources often appear as mixtures of several molecular sideband beams. This fragmentation process leads to dilution of the intensity of the species of interest for radioactive ion beam (RIB) applications where beam intensity is at a premium. We have conceived an ion source that combines the excellent molecular dissociation properties of a thermal dissociator and the high ionization efficiency characteristics of an electron impact ionization source that will, in principle, overcome this handicap. The source concept will be evaluated as a potential candidate for use for RIB generation at the Holifield Radioactive Ion Beam Facility, now under construction at the Oak Ridge National Laboratory. The design features and principles of operation of the source are described in this article.

1. Abstract of published paper: *Rev. Sci. Instrum.* **67**, 1626 (1996).
2. Gilbert/Commonwealth Engineers & Consultants, Oak Ridge, TN.

A HIGH-EFFICIENCY POSITIVE (NEGATIVE) SURFACE IONIZATION SOURCE FOR RIB GENERATION[1]

G. D. Alton and G. D. Mills

A versatile, new concept, spherical-geometry, positive (negative) surface-ionization source has been designed and fabricated which will have the capability of generating both positive- and negative-ion beams without mechanical changes to the source. The source utilizes a highly permeable, high-work-function Ir ionizer ($\phi \equiv 5.29$ eV) for ionizing highly electropositive atoms/molecules; while for negative-surface ionization, the work function is lowered to $\phi \equiv 1.43$ eV by continually feeding cesium vapor through the ionizer matrix. The use of this technique for negative ion beam generation has the potential of overcoming the chronic poisoning effects experienced with LaB_6 while enhancing considerably the efficiency for negative surface ionization of atomic and molecules with intermediate electron affinities. The flexibility of operation in either mode makes it especially attractive for RIB applications and, therefore, the source will be used as a complementary replacement for the high-temperature electron impact ionization sources presently in use at the HRIBF. The design features and operational principles of the source will be described in this report.

1. Abstract of published paper: *Rev. Sci. Instrum.* **67**, 1630 (1996).

EFFUSIVE FLOW DELAY TIMES FOR GASEOUS SPECIES IN A COMPACT RF ION SOURCE[1]

R. F. Welton,[2] A. Piotrowski,[3] G. D. Alton, S. N. Murray

A rf ion source is presently being developed and evaluated as a potential candidate for use in generating radioactive ion beams (RIBs) for the experimental research program at the Holifield Radioactive Ion Beam Facility (HRIBF) now under construction at the Oak Ridge National Laboratory . For this application, any time delays that are excessively long with respect to the half-life of the radioactive species of interest can result in significant losses of the RIB intensity; therefore, the time for effusive flow through the ion source are of fundamental importance since they set limits on the minimum half-life of radioactive species that can be processed in the source. Complementary experimental and computational techniques have been developed which can be used to determine the characteristic delay times for gaseous species in low-pressure ion source assemblies. These techniques are used to characterize the effusive delay time for the stable counterparts of various atomic and molecular radioactive species in the ORNL-rf source: He, Ne, Ar, Kr, Ze, H_2, CO, CO_2, N_2, N_2O, and O_2.

1. Abstract of published paper: *Rev. Sci. Instrum.* **67**, 1670 (1996).

A SINGLE-FREQUENCY ECR ION SOURCE WITH A LARGE UNIFORMLY DISTRIBUTED RESONANT PLASMA VOLUME[1]

G. D. Alton, D. N. Smithe[1]

An innovative technique for increasing ion source intensity is described which, in principle, could lead to significant advances in ECR ion source technology for multiply charged ion beam formation. The advanced concept design uses a minimum-B magnetic mirror geometry which consists of a multi-cusp, magnetic field, to assist in confining the plasma radially, a flat central field for tuning to the ECR resonant condition, and specially tailored mirror fields in the end zones to confine the plasma in the axial direction. The magnetic field is designed to achieve an axially symmetric plasma "volume" with constant mod-B, which extends over the length of the central field region. This design, which strongly contrasts with the

ECR "surfaces" characteristic of conventional ECR ion sources, results in dramatic increases in the absorption of RF power, thereby increasing the electron temperature and "hot" electron population within the ionization volume of the source.

1. Abstract of published paper: *Proceedings, Twelfth International Workshop on ECR Ion Sources, Wako-shi, Japan, April 25-27, 1995*, pp. 100 ff.
2. Mission Research Corporation, 8560 Cinder Bed Road, Suite 700, Newington, VA 22122.

SELECTION AND DESIGN OF ION SOURCES FOR USE AT THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

G. D. Alton, D. L. Haynes, G. D. Mills, D. K. Olsen

The Holifield Radioactive Ion Beam Facility now under construction at the Oak Ridge National Laboratory will use the 25 MV tandem accelerator for the acceleration of radioactive ion beams to energies appropriate for research in nuclear physics; negative ion beams are, therefore, required for injection into the tandem accelerator. Because charge exchange is an efficient means for converting initially positive ion beams to negative ion beams, both positive and negative ion sources are viable options for use at the facility. The choice of the type of ion source will depend on the overall efficiency for generating the radioactive species of interest. Although direct-extraction negative ion sources are clearly desirable, the ion formation efficiencies are often too low for practical consideration; for this situation, positive ion sources, in combination with charge exchange, are the logical choice. The high-temperature version of the CERN-ISOLDE positive ion source has been selected and a modified version of the source designed and fabricated for initial use at the facility because of its low emittance, relatively high ionization efficienceies, and species versatility, and because it has been engineered for remote installation, removal, and servicing as required for safe handling in a high-radiation-level ISOL facility. The source will be primarily used to generate ion beams from elements with intermediate to low electron affinities. Prototype plasma-sputter negative ion sources and negative surface-ionization sources are under design consideration for generating radioactive ion beams from high-electron-affinity elements. The design features of these sources and expected efficiencies and beam qulaities (emittances) will be described in this report.

1. Abstract of published paper: *Rev. Sci. Instrum.* **65**, 2012 (1994).

DESIGN FEATURES OF A HIGH-INTENSITY, CESIUM-SPUTTER/PLASMA-SPUTTER NEGATIVE ION SOURCE[1]

G. D. Alton, G. D. Mills, J. Dellwo[2]

A versatile, high-intensity, negative ion source has been designed and is now under construction which can be operated in either the cesium-sputter of plasma-sputter mode. The cesium-sputter mode can be effected by installation of a newly designed conical-geometry cesium-surface ionizer; for operation in the plasma-sputter mode, the surface ionizer is removed and either a hot filament or rf antenna plasma-discharge igniter is installed. A multicusp magnetic field is specifically provided confining the plasma in the radial direction when the plasma-sputter mode is selected. This arrangement allows comparison of the two modes of operation. Bried descriptions of the design features, ion optics, and anticipated performances of the two source geometries will be presented in this report.

1. Abstract of published paper: *Rev. Sci. Instrum.* **65**, 2006 (1994).
2. Partial support from the Joint Institute for Heavy Ion Research, Oak Ridge, TN.

HIGH-INTENSITY, HEAVY NEGATIVE ION SOURCES BASED ON THE SPUTTER PRINCIPLE[1]

G. D. Alton

Due to their ease of operation, simplicity, long lifetime, and wide range of species capabilities, negative ion sources predicated on the sputter principle are being used for an increasing number of diverse applications. Sources based on this technology have been developed which utilize either direct cesium-surface ionization, or a plasma seeded with cesium to form positive ion beams for sputtering sample materials from which negative ion beams are generated. This article will include a brief review of the fundamental processes underlying negative ion formation by the sputter technique, as well as describe a selected number of recent ion source developments which exemplify the state-of-the-art of this technology.

1. Abstract of published paper: *Rev. Sci. Instrum.* **65**, 1141 (1994).

THE STRIPPING PROPERTIES OF A PLASMA: COMPUTATIONAL STUDIES[1]

G. D. Alton, R. A. Sparrow,[2] R. E. Olson[2]

The n-Body Classical Trajectory Monte Carlo (n-CTMC) model[3,4] has been utilized to determine the feasibility of a plasma stripper as a possible alternative to the gaseous and foil strippers which are commonly used to enhance the charge states of energetic ion beams. The idea is based on the knowledge that (1) stopping powers (energy loss per unit path length) are greater for a plasma than a gaseous stripper at equivalent line densities and (2) the number of electron channels available for capture by the projectile are reduced when the target is ionized. In this paper, we evaluate the merits of a plasma as a heavy ion stripper by comparing calculated charge state distributions which result during passage of 20-MeV Pb^- projectiles through a number of neutral and ionized targets, including Mg^0 and Mg^+, Li^0 and Li^+, and H_2^0 and H^+. We predict only modest increases in most probable charge state for heavy multi-electron, fully ionized (singly) plasma targets over their respective neutral target counterparts. This behavior is attributable to the large number of electrons which remain on the target atoms and the relatively high cross sections for capture of these electrons by the projectile. The most probable charge states, however, for a low-atomic-number target such as Li^+ are found to increase by two units relative to Li^0 at the same line density due to the decrease in cross sections for K-shell capture by the projectile. A fully ionized H^+ plasma is obviously the best choice for a stripper because there are essentially no channels available for electron capture by the projectile and the angular scattering of the projectile in the laboratory system is considerably reduced over that resulting from the use of a higher Z_2 target. As a consequence, a hydrogen plasma stripper does not reach a limiting equilibrium charge state distribution for plasma line densities up to $10^{20}/cm^2$ as is found for neutral and singly charged higher Z^2 plasma strippers. Higher charge states can be achieved by simply increasing the line density. The results of these simulation studies are complementary to the findings of Hoffmann et al[5] who have experimentally observed relatively large increases in projectile energy losses in fully ionized hydrogen plasmas over those for neutral hydrogen targets at line densities up to $10^{19}/cm^2$. From these studies, we clearly demonstrate that a fully ionized (singly), low-atomic-number plasma target such as hydrogen can be more effective as a stripper than a gaseous target of the same density.[6]

1. Abstract of published paper: *Proceedings, The Second International Conference on Computational Physics (ICCP-2) Beijing, China, Sept. 13-17, 1993,* International Press, Hong Kong, pp. 541-50 (1995).
2. University of Missouri, Rolla.
3. R. E. Olson, J. Ullrich and H. Schmidt-Böcking, *Phys. Rev. A* **39**, 5572 (1989).
4. C. O. Reinhold, R. D. Schultz, R. E. Olson, L. J. Roburen, and R. D. Dubois, *J. Phys. B: At. Mol. Opt. Phys.* **23**, L197 (1990).

5. D. H. H. Hoffmann, K. Weyrich, H. Wahl, D. Gardnes, R. Bimbot, and C. Fleurier, *Phys. Rev. A* **42**, 2313 (1990).
6. G. D. Alton, R. A. Sparrow, and R. E. Olson, *Phys. Rev. A* **45**, 5957 (1992).

TARGET SELECTION FOR THE HRIBF PROJECT[1]

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Experiments are in progress at the Oak Ridge National Laboratory (ORNL) which are designed to select the most appropriate target materials for generating particular radioactive ion beams for the Holifield Radioactive Ion Beam Facility (HRIBF). The 25-MeV tandem accelerator is used to implant stable complements of interesting radioactive elements into refractory targets mounted in a high-temperature FEBIAD ion source which is on-line at the UNISOR facility. These experiments permit selection of the target material most appropriate for the rapid release of the element of interest, as well as realistic estimates of the efficiency of the FEBIAD source. From diffusion release, data information on the release times and diffusion coefficients can be derived. Diffusion coefficients for Cl implanted into and diffused from CeS and Zr_5Si_3 and As, Be, and Se implanted into and diffused from Zr_5Ge_3 have been derived from the resulting intensity versus time profiles.

1. Abstract of published paper: *Nucl. Instrum. Meth. Phys. Res. B* **99**, 335-337 (1995).
2. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
3. Louisiana State University, Baton Rouge.
4. UNISOR, Oak Ridge Institute for Science and Education, Oak Ridge.
5. New York State College of Ceramics at Alfred University, Alfred.
6. LNS, Catania, Italy.
7. JAERI, Japan.
8. Georgia Technological University, Atlanta.

ROTATIONAL BANDS IN ^{76}Rb (Ref. 1)

A. Harder,[2] M. K. Kabadiyski,[2] K. P. Lieb,[2] D. Rudolph,[2] C. J. Gross,[3] R. A. Cunningham,[4] F. Hannachi,[4] J. Simpson,[4] D. D. Warner,[4] H. A. Roth,[5] Ö. Skeppstedt,[5] W. Gelletly,[6] B. J. Varley[7]

High spin states in ^{76}Rb were investigated via the reaction ^{40}Ca(^{40}Ca,^{3}pn)^{76}Rb at 128 MeV. The level scheme was established from $\gamma\gamma$, $\gamma\gamma\gamma$ and recoil-γ coincidences measured in the EUROGAM I array in combination with the Daresbury recoil separator. The known rotational bands were extended up to the excitation energy $E_x \approx 9.2$ MeV and spins $I^\pi = (21^+)$ and (19^-). The band head energies could be fixed by many interband transitions. Two new bands were identified. The level scheme is discussed in terms of the cranked shell model. In the negative parity bands ^{76}Rb behaves like a rigid rotor until the first band crossings.

1. Abstract of published paper: *Phys. Rev. C* **51**, 6 (1995).
2. Physikalisches Institut, Germany.
3. ORISE/ORNL, Oak Ridge, TN.
4. Dares bury Laboratory, United Kingdom.
5. Chalmers University of Technology, Sweden.
6. University of Surrey, United Kingdom.
7. University of Manchester, United Kingdom.

A NEW TYPE OF BAND CROSSING AT LARGE DEFORMATION[1]

A. Harder,[2] F. Dönau,[3] K. P. Lieb,[2] R. A. Cunningham,[4] W. Gelletly,[5] C. J. Gross,[6] F. Hannachi,[2,4] M. K. Kabadiyski,[2] H. A. Roth,[7] D. Rudolph,[2,3] J. Simpson,[4] Ö. Skeppstedt,[7] B. J. Varley,[8] D. D. Warner[4]

A detailed study of the positive parity yrast and yrare rotational bands in ^{77}Rb is presented. Using the reaction ^{40}Ca(^{40}Ca,3*p*) and the EUROGAM I spectrometer, $\gamma\gamma\gamma$ coincidences enabled us to follow both bands over a large spin range and to measure many E2 strengths. The moments of inertia and transition quadrupole moments indicate that a more deformed band ($\varepsilon_2 \approx 0.38$) is crossed by a less deformed one ($\varepsilon_2 \approx 0.29$). Since the yrare band starts at the extremely low spin value of $I = 9/2$, the conventional band crossing mechanism of two aligning high-j quasiparticles is excluded. The frequency-dependent equilibrium shapes were calculated with Nilsson-Strutinsky type calculations using a diabatic tracing of configurations near the neutron Fermi level. This is the first observation of such a band crossing.

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1. Abstract of published paper: *Phys. Lett.* B **374**, 277-282 (1996).
2. Universität Göttingen, Göttingen, Germany.
3. Institut für Kern-Hadronenphysik, Dresden, Germany.
4. Daresbury Laboratory, Warrington, United Kingdom.
5. University of Surrey, Guildford, United Kingdom.
6. ORISE/ORNL, Oak Ridge, TN.
7. Chalmers University of Technology, Göteborg, Sweden.
8. University of Manchester, Manchester, United Kingdom.

2. NUCLEAR STRUCTURE AND ASTROPHYSICS

OVERVIEW

A cutting-edge experimental research program in nuclear structure and nuclear reactions has given Physics Division a strong background in traditional nuclear physics for many years. This program has been concentrated on the spectroscopy of rapidly-rotating nuclei, giant resonance studies, and reaction dynamics. With the incorporation of astrophysics research centered around the ORELA Facility and with the advent of the new Holifield Radioactive Ion Beam Facility (HRIBF), this program has become even stronger during the period of this report. Even during a time when all the research groups are making contributions to the preparation of the HRIBF and its ancillary equipment, the existing research program has continued. For example, the nuclear structure group has led the characterization of the mass eighty region of superdeformed nuclei and has initiated studies of deformed (and searches for superdeformed) states in lighter nuclei. The nuclear reactions group has extended the giant resonances program to studies of exotic nuclei by measurements of the E1 strength function in ^{11}Be to over 20 MeV. At ORELA, neutron-capture measurements, critical for the characterization of slow-neutron capture process (s-process), nucleosynthesis, and precision measurements of the polarizability of the neutron have been made. Reports of these and other nuclear structure and astrophysics projects are reported in this section. Many of these experimental studies are designed to characterize the physical phenomena which can be addressed in greater detail using the early proton-rich radioactive ion beams from the HRIBF.

The nuclear structure group has taken the leadership in the installation and commissioning of a state-of-the-art Recoil Mass Separator (RMS) and its associated detector systems. This system is operational with focal plane detectors available for alpha, beta, gamma, and proton decay of the reaction products. The nuclear structure group also is involved in a major upgrade of the detector arrays at the target position of the RMS. These arrays will be used establish the prompt gamma-ray cascade and as well as the prompt emission of protons, neutrons, and alpha particles from the reaction products. The first phase of the upgraded target station arrays should be operational in 1997.

Likewise, the nuclear astrophysics group is involved in the installation of the Daresbury Recoil Separator (DRS) which has been transferred from Daresbury Laboratory in the U.K. to ORNL. This instrument, which will soon be commissioned, will form the basis of an astrophysics experimental station at the HRIBF. The ORNL astrophysics group will use this device to lead a multilab effort to study reactions important for rapid-proton capture process (rp-process) explosive nucleosynthesis.

The reactions spectroscopy group plans to continue their initial program of studies of the giant resonance of exotic nuclei using the intermediate energy radioactive ion beams at the Michigan State University National Superconducting Cyclotron Laboratory.

The staff of the Nuclear Structure and Astrophysics Research Section is dedicated to maintaining effective and creative state-of-the-art research programs while facing the challenge of preparing major new experimental equipment and redirection of their research programs.

NUCLEAR STRUCTURE

HIGH-SPIN STATES IN ^{52}Fe

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High–spin states in ^{52}Fe were populated and studied as part of the GAMMASPHERE measurement with the MICROBALL using the ^{28}Si(^{36}Ar,3α) reaction at 136 MeV. A total of 2 billion events were recorded, with the 3–α–decay channel leading to ^{52}Fe representing only 0.03% of the data. The purpose of this measurement was to study the structure of nuclei along the N = Z line, which for this case is N = Z = 26.

Our analysis has led to the assignment of 24 gamma rays to a scheme of 16 levels extending to a spin of 12 and an energy of 10.4 MeV. A 12^+ isomeric state was observed in an earlier measurement,[7] but here we concentrated on the prompt events. Previous works[8-11] assigned a more limited set of levels than found here. We assign yrast states at 0.849, 2.385, 4.327, 6.364, and 8.374 MeV for the I = 2^+ through 10^+ states, based on our coincidence and directional correlation of oriented nuclei (DCO) analyses.

The non–yrast levels provide a challenge to the theoretical understanding of this N = Z nucleus. Two non–yrast 6^+ levels are seen at an excitation energy of 4.874 and 5.656 MeV. These energies and those of the yrast states agree well with the shell model calculations made in the fp–configuration space. These calculations were performed using two different realistic interactions (FPD6 and KB3[12]), allowing up to four particles out of the $f_{7/2}$ sub–shell and unrestricted interactions in the rest of the space. Of special interest are states observed at 4.403 and 5.143 MeV, which are connected by a 740-keV E2 transition. The DCO analysis cannot yet specify if these states have spins of 3^- and 5^- respectively, of 4^+ and 6^+. Either scenario is difficult to understand in the limit of only f and p shell states being available. In the latter scenario, a fourth low–lying 6^+ state is not understood, as the shell model calculations predict that the fourth 6^+ state should be at 6.2 MeV, not as low as 5.143 MeV. In the case of a 5^- assignment for this state, the $g_{9/2}$ state must be included in the calculations to give any negative–parity level. The location of the $g_{9/2}$ single-particle state is not experimentally known, so our possible observation of negative–parity states at 4.4 to 5.1 MeV would be important for its identification.

Experimental and theoretical analyses are continuing.

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HIGH-SPIN γ-RAY SPECTROSCOPY IN THE VICINITY OF ^{56}Ni

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The nuclei located near the doubly magic shell gap N = Z = 28 have been extensively studied with light-ion-induced reactions (e.g., Ref. 6 for the isospin $T_z = +1/2$ nucleus ^{55}Co). The $B(E2;2^+ \rightarrow 0^+)$ in ^{56}Ni was measured recently[7] with a proton-scattering experiment in inverse kinematics. The comparatively large value can be explained by the attractive interaction of $1f_{7/2}$ holes and $1f_{5/2}$ or $2p_{3/2}$ particles. However, very little high-spin spectroscopy data presently exists in the mass A ≈ 60 region. Research objectives in this mass region are: to constrain the spherical shell-model parameters, to observe the predicted normal deformed and possibly superdeformed rotational bands to study the influence of the $T = 0$ pairing in (odd-odd) $N = Z$ systems, and to test of the isospin symmetry in medium-mass mirror nuclei.

We performed an experiment using the heavy-ion induced reaction ^{36}Ar + ^{28}Si at 136 MeV beam energy at the GAMMASPHERE facility in conjunction with ancillary detectors to measure the evaporated neutrons, protons, and α-particles. Nearly 2 x 10^9 and 3 x 10^8 two- to four-fold gamma events were collected with thin and Ta-backed targets, respectively.

The first experimental results include the identification of γ rays originating from the $T_z = -1/2$ nucleus ^{55}Ni. This nucleus was produced via ^{28}Si(^{36}Ar,2α*n*)^{55}Ni with an experimental partial cross-section of $\sigma \approx 0.004\%$. After subtracting contaminations from higher-fold charged-particle channels (e.g., ^{54}Co + 2α*pn*) or small target impurities (<1% ^{29,30}Si), ≈ 200 counts are left in the peak of the 2882-keV ground-state transition which corresponds to a channel selection of the order of 10^{-7}. The excitation energy of 2882 keV probably corresponds to a state at 2888(7) keV observed in the ^{58}Ni(^{3}He,^{6}He)^{55}Ni reaction.[8] A spectrum gated by this 2882 keV transition clearly shows coincidences with the γ rays at 701, 735, and 866 keV. The mirror symmetry of the two A = 55, T = 1/2 nuclei can clearly be seen in the schemes presented in Fig. 2.1. Only three transitions were reported previously for ^{55}Co. Our preliminary level scheme comprises ≈ 70 γ rays connecting ≈ 35 near yrast levels up to $I \approx 18\hbar$ at 15 MeV excitation energy. Completely aligned seniority $v = 7$ configurations in the *fp* shell are compatible with these values. Other results include extended level schemes of the odd-odd N = Z nuclei ^{54}Co and ^{58}Cu providing information about the T = 0 two-body matrix-elements of a *np* hole or *np* pair relative to ^{56}Ni.

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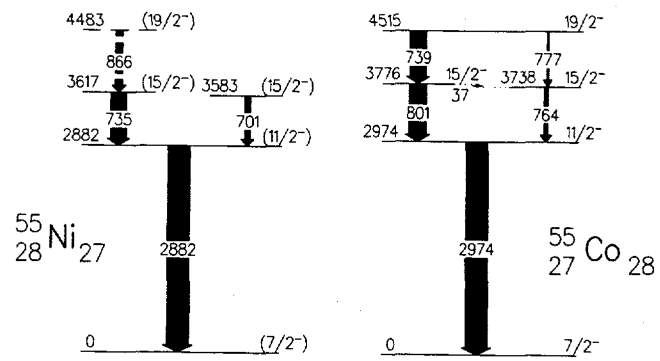

Fig. 2.1. Partial excitation schemes of ^{55}Ni and ^{55}Co.

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THE SPECTROSCOPY OF ^{60}Ni

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High-spin states in ^{60}Ni were populated using the ^{28}Si(^{36}Ar,4*p*) reaction with a beam energy of 136 MeV. The ^{39}Ar beam, which bombarded a 0.42 mg/cm^2 ^{28}Si target, was supplied by the LBNL 88" cyclotron. GAMMASPHERE was used in conjunction with the MICROBALL to detect gamma rays in coincidence with various combinations of detected protons and alpha particles. At the time of this measurement, GAMMASPHERE contained 82 Compton-suppressed Ge detectors, MICROBALL had the usual array of 95 CsI counters, and 15 neutron detectors were mounted at forward angles. A total of 2 billion events were recorded, with the 4*p* channel leading to ^{60}Ni representing approximately 11% of the data.

Previous data on ^{60}Ni led to the assignment of yrast states up to an energy of 6.804 MeV with a spin of 9^+.[7] In our analysis, yrast states have been extended to an energy of 12.7 MeV with a possible spin of 16, and so far a total of 38 levels have been established. Further work on assignment of levels and placement of gamma lines is continuing, as is a detailed analysis of DCO ratios necessary for the assignments of spins and parities. The previous work had attempted a theoretical analysis of the lower spin structure in terms of ground, gamma, and beta vibrational bands.[7] Shell model calculations in this region require inclusion of the $g_{9/2}$ single-particle orbital into the fp-shell model space. Large-scale calculations have not been previously carried out in this region to compare to the experiment. We, together with D. J. Dean of the nuclear group, will develop an appropriate interaction for this region and apply it to ^{60}Ni. Once the shell structure of this nucleus is understood, we can proceed to the question of whether there is evidence for collective effects.

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"SUPERDEFORMED" BANDS IN ^{80}Sr

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Superdeformed bands have been observed in numerous nuclei in the mass 80 region in recent years. The lightest of these nuclei is ^{80}Sr, for which we report here the observation of four high-spin collective bands.

The nucleus ^{80}Sr was populated by the reaction ^{58}Ni(^{28}Si,$\alpha\, 2p$) at E_{lab} = 130 MeV, and GAMMASPHERE with 57 detectors was used to detect γ rays in triple or higher coincidence. The MICROBALL, an array of 95 CsI detectors, was used to select charged-particle exit channels. The γ rays were Doppler corrected using the recoil momentum reconstructed from the observed evaporation products, in order to obtain the best possible γ-energy resolution.

Figure 2.2 shows the four observed SD bands, double-gated on all of the transitions (marked by asterisks) in the bands. The observed coincident evaporation particles and low-spin γ rays indicate that all of these bands are in ^{80}Sr, though no connecting transitions have been established. Futher, band 3 appears to decay into band 2, and band 2 splits at higher spins. The dynamic moments of inertia of all the bands are approximately 24 $\hbar^2$/MeV.

Lifetime measurements of the two strongest bands were made using the centroid-shift method, and average transition quadrupole moments (Q_t) were extracted. These bands appear to be considerably less deformed than SD bands in other Sr isotopes.[6] Figure 2.3 shows the extracted average Q_t values for the yrast SD bands in Sr isotopes, as well as that for the ground bands at low spin.[7] As can be seen, the deformation of the yrast SD band in ^{80}Sr is significantly less than that in the other Sr isotopes, and is approximately equal to that of its normal deformed ground band at low spin.

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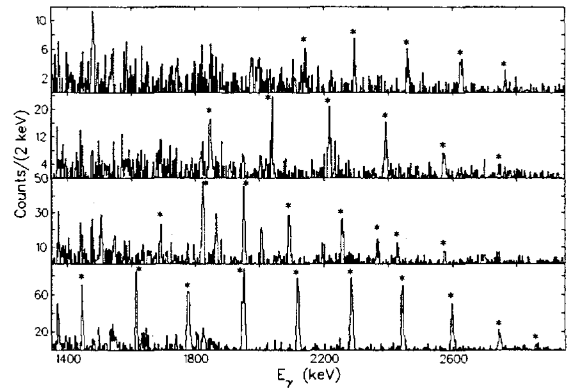

Fig. 2.2. SD bands 1 (bottom) to 4 (top) observed in ^{80}Sr.

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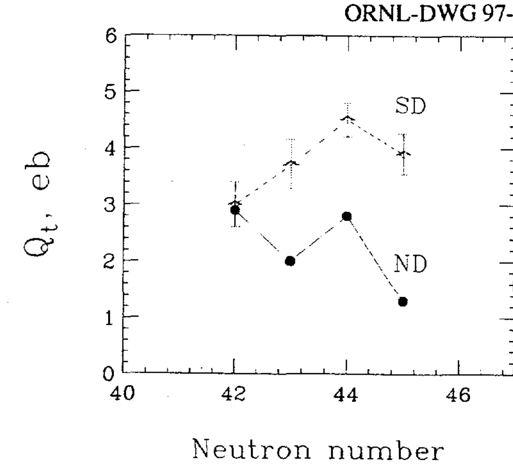

Fig. 2.3. Average Qt values for SD and low-spin normal deformed yrast bands in Sr isotopes.

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TWINNED IDENTICAL SUPERDEFORMED BANDS IN THE A = 80 REGION: A FURTHER PROBE OF NUCLEAR DEFORMATION

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Since the report of the first superdeformed (SD) band in the medium-mass nucleus ^{83}Sr,[7] nearly 20 new SD bands have been discovered in the A = 80 region. Here, we report the first observation of twinned identical SD bands in this region. Such SD bands, first observed in the A = 150 region, may be attributed to the presence of K = 1/2 single-particle orbitals with decoupling parameter a = 1 near the Fermi surface.[8]

Two experiments were performed at the LBNL 88" cyclotron with the GAMMASPHERE spectrometer and the "MICROBALL" charged-particle detector system. Fusion-evaporation reactions ^{58}Ni(^{28,29}Si,3p)^{83,84}Y at beam energies of 130 and 128 MeV, respectively, were used. Steps of data analysis included kinematical corrections of recoils, proper charged-particle gatings, and the removal of contaminating channels. Two of the SD bands established in ^{83}Y and ^{84}Y were found to have nearly identical γ-ray energies to two SD bands in their isotones ^{82}Sr (Ref. 9) and ^{83}Sr, respectively. Figure 2.4 illustrates the identification of the band in ^{83}Y by removing the contamination from ^{82}Sr.

To understand the nature of the identical SD bands in the A = 80 region, we have performed Nilsson-Strutinsky cranking calculations for several sets of shape parameters. The [310]1/2$^-$ proton orbital, which offers a natural explanation for these identical bands, approaches the Fermi surface for Z ~ 39 at deformations of $\beta_2 \simeq 0.5$. The location of this orbital, however, is very sensitive to the deformation parameters assumed in the calculations. The presence of these identical bands, therefore, may be used to further constrain the deformation parameters deduced from lifetime measurements. Lifetime measurements for a second SD band in ^{83}Y indicate that its Q_t value is similar to that for ^{82}Sr, but smaller than the value for ^{84}Zr.[10]

ORNL-DWG 97-5426

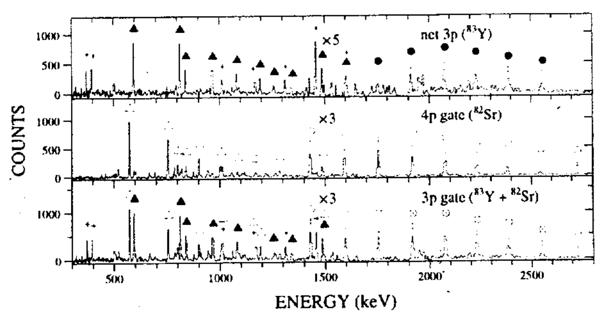

Fig. 2.4. Spectra obtained by double gating on transitions in the SD bands of ^{82}Sr (4p gated, middle) and ^{83}Y (3p with contamination from 4p, bottom). The normalized difference (top) shows the clean SD spectrum in ^{83}Y. Transitions from ND bands are indicated by filled triangles (^{83}Y), opened triangles (^{82}Sr), and stars (^{82}Y).

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7. C. Baktash et al., *Phys. Rev. Lett.* **74**, 1946 (1995).
8. W. Nazarewicz et al., *Phys. Rev. Lett.* **64**, 1654 (1990).
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HIGH-SPIN SPECTROSCOPY OF ^{80,81}Sr

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Data from a recent GAMMASPHERE experiment is being analyzed to study the high-spin properties of ^{80}Sr and ^{81}Sr. The reaction used was ^{28}Si on ^{58}Ni at a beam energy of 130 MeV. The MICROBALL was used for particle identification and for kinematic correction of Doppler broadening. Analysis of these data at the University of Pittsburgh is underway, and a preliminary report of the results was given at a recent APS meeting.[7]

The last published study of high-spin states in ^{80}Sr was by Davie et al.[8] in 1987. That work found four rotational bands, the strongest one extending to a spin of $26\hbar$. Lifetime measurements indicated that the transitions are collective up to the highest spins observed. Of particular interest was an unexplained staggering in the moment of inertia $\Im^{(1)}$ of the ground state band.

To date, our work in ^{80}Sr has added many states and several new bands to the level scheme reported in Ref. 8. Our decay scheme for the high-spin portion is somewhat different than given in the previous work. For example, the observed staggering in $\Im^{(1)}$ does not occur. Analysis of the angular distributions of gamma rays is underway in order to establish multipolarities and mixing ratios. Careful analysis of these quantities, along with lifetime measurements, allow a deeper investigation of nuclear structure than do simple coincidence measurements. Angular distribution measurements are possible with this data set due to the good statistics obtained at several angles, combined with the ability to produce clean singles spectra with particle gates.

Above a spin of about $22\hbar$, many of the bands show a large degree of branching and a decrease in the moment of inertia at the highest spins, both signs of possible band terminations. In order for band termination to be observable, there must be enough valence particles to form a collectively rotating band, but few enough that the band is within an observable range. Nazarewicz and co-workers predict several terminating bands in ^{80}Sr in the spin range $22\hbar$ to $46\hbar$.[9] Evidence for the onset of band termination in ^{82}Sr has been reported by Cullen and co-workers.[10] While it is too early to say conclusively that band termination has been observed in ^{80}Sr, the preliminary results are encouraging. A theoretical analysis of the phenomenon will be undertaken. In the future, we hope to extend the investigation of band termination to other nuclei in the region.

While the analysis of the normally deformed structure of ^{81}Sr is not as advanced as for ^{80}Sr, preliminary work has already added several bands and levels to what has previously been reported.[11,12] As with ^{80}Sr, angular distribution data will be analyzed. For both Sr isotopes, some of the data was taken using a backed target. This will allow the determination of lifetimes using the Doppler-shift attenuation method.

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RESOLUTION-ENHANCED SPECTROSCOPY OF ^{81}Y

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The fusion-evaporation reaction ^{58}Ni(^{32}S, 2αp) has been used to study the neutron-deficient isotope ^{81}Y. Multiple particle-γ-ray coincidences have been detected using the GAMMASPHERE array combined with the MICROBALL charged-particle detector system.

Gamma-ray spectra with an improved resolution have been achieved from an event-by-event determination of the nucleus recoil momentum, thus allowing a precise Doppler-shift correction.

The gain in gamma-ray energy resolution compared to conventional Doppler-shift correction is shown in Fig. 2.5, e.g., the resolution of a 1 MeV γ-line is improved by a factor of 2, to less than 6 keV. It should be noted that the improvement in energy resolution is accompanied by a simultaneous enhancement in the peak-to-background ratio in the observed γ-spectra. Furthermore spectra with less contaminating γ-lines are produced as the consequence of a more precise placement of the coincidence window.

During the analysis an E_γ-E_γ matrix as well as an E_γ-E_γ-E_γ cube have been used to extend the previously known level scheme to higher spin (I ~ 57/2) and excitation energy (E_x~17 MeV). More than 100 new γ rays and 80 new levels have been added to the level scheme and six new bands have been established.

ORNL-DWG 97-5498

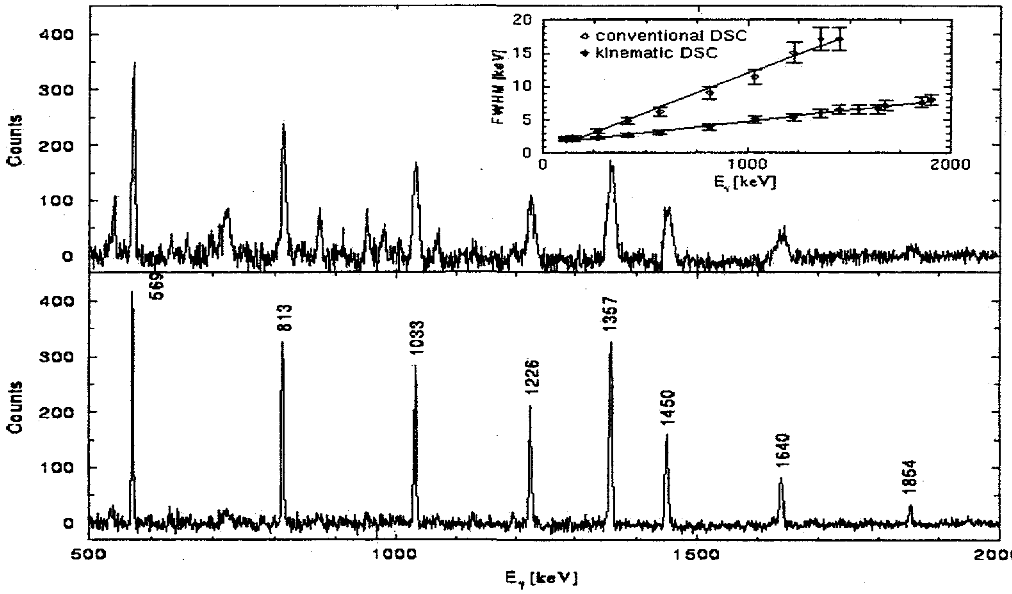

Fig. 2.5. Comparison of two coincidence spectra before (top) and after kinematic Doppler-shift correction (bottom). The coincidence window was set on the 41/2$^+$ → 37/2$^+$ 1515 keV γ-line. The inset shows the energy resolution of observed γ-lines, as function of E_γ for conventional and kinematic Doppler-shift correction.

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LIFETIMES OF DEFORMED AND SUPERDEFORMED STATES IN ^{82}Sr

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^{82}Sr is one of the first mass 80 nuclei for which superdeformed (SD) bands were observed.[7] This nucleus was also suggested to exhibit shape coexistence[8] and band terminations at high spins.[9,10] Indeed, calculations have predicted prolate, oblate and triaxial normal deformed bands in this nucleus.[8] In order to confirm such a wide range of variations in deformation in one nucleus, we carried out an experiment at the GAMMASPHERE to measure lifetimes of both superdeformed and normally deformed states in ^{82}Sr.

High-spin states in ^{82}Sr were populated using the ^{58}Ni(^{28}Si, 4p) reaction at E_{beam} = 130 MeV. The γ rays and protons were detected by 57 Ge detectors of the GAMMASPHERE and the MICROBALL. A total of about 97 million and 17 million 4π-gated, γ-γ-γ coincidence events were collected from thin-target and backed-target runs, respectively. From the thin-target run, the previously observed[7] SD band 1 was confirmed, and an average lifetime was measured using the Centroid Shift Method. The extracted $F(\tau)$ values for SD band 1 and one of the normal deformed (ND) bands are shown in Fig. 2.6 together with the calculated curves of various quadrupole moments (Q_t's). An average Q_t of 4.5 eb fits the data best. This value is about 13% smaller than the measured[11] Q_t for the SD band in its neighboring isotone, ^{84}Zr.

The backed-target run allowed the extraction of lifetimes of high-spin states in three normally deformed rotational bands using the standard DSAM technique. The measured Q_t's for the yrast band and two negative-parity bands are shown in Fig. 2.7. This figure shows that the average Q_t of the yrast band is about 30% smaller than those for the two negative-parity bands. This is consistent with theoretical predictions of an oblate shape for the yrast band and triaxial shape for the negative-parity bands. At high angular momentum, the Q_t's for the yrast band and one negative-parity band decrease with increasing spin, supporting the previous suggestion that band termination sets in at high spins in these rotational bands.

ORNL-DWG 97-5437

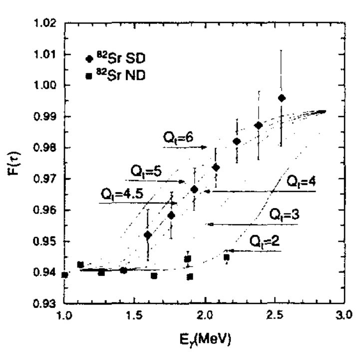

Fig. 2.6. Experimental $F(\tau)$ values for the SD band (circles) and one ND band (squares) together with calculated curves of various Q_t's.

ORNL-DWG 97-5438

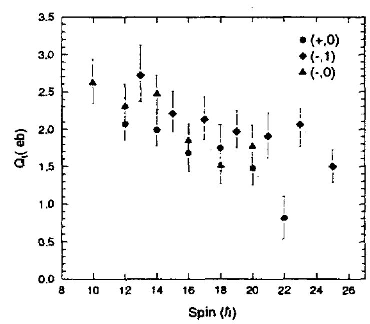

Fig. 2.7. Experimental Q_t values for the three ND bands extracted using the DSAM technique.

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SUPERDEFORMATION IN ONE OR MORE PM ISOTOPES

M. J. Brinkman, H.-Q. Jin, C. Baktash, R. M. Clark,[1] M. Devlin,[2] P. Fallon,[1] D. R. LaFosse,[2] I. Y. Lee,[1] F. Lerma,[2] A. O. Macchiavelli,[1] D. Rudolph, D. G. Sarantites,[2] and C.-H. Yu

Lying midway beween the A ~ 130 island of highly deformed nuclei and the A ~ 150 island of superdeformation, the high–spin structure of the $60 \leq Z \leq 64$ nuclei may provide a suitable laboratory for studying the evolution of nuclear shapes at large deformation and high spin. To date, however the only known examples of superdeformed (SD) structures in this mass region are found in the ^{142,143,144}Sm[3,4] isotopes. We have been able to identify three distinct SD rotational bands in one or more of the Pm nuclei.

The data used in this analysis was collected following the bombardment of a thin self–supporting ^{100}Mo target by a 205–MeV beam of ^{48}Ca. The data were collected using a fifty–eight detector version of GAMMASPHERE and the 95-element MICROBALL charged-particle detection array. This experiment was designed to search for hyperdeformation in the heavier Sm isotopes; as such, events were written to tape only when four or more Compton-suppressed Ge detectors fired in coincidence. During this run slightly fewer than 2.5 x 10^9 events were recorded using this trigger condition. Approximately 5% of all events arose from the γ–ray deexcitation of Pm isotopes, as determined by coincidence with a single evaporation proton.

In Fig. 2.8 provided below, we present the spectrum of the strongest of the three superdeformed bands found in this work. The Pm bands share markedly similar characteristics with the SD bands observed in the Sm nuclei,[3,4] with dynamic moments of inertia that are relatively flat and centered at ~65 $\hbar^2$/MeV. As can be seen from the spectrum provided, these SD structures are weakly populated in our data set. This can be attributed to two factors: 1) the partial Pm production cross section is only 1/20 that of the total reaction cross–section, and 2) the Pm nuclei are odd–Z with the most strongly populated nucleus the odd–odd ^{140}Pm. Due to the low intensity of these bands, we have been unable to make an unambiguous nuclear assignment.

ORNL-DWG 97-5442

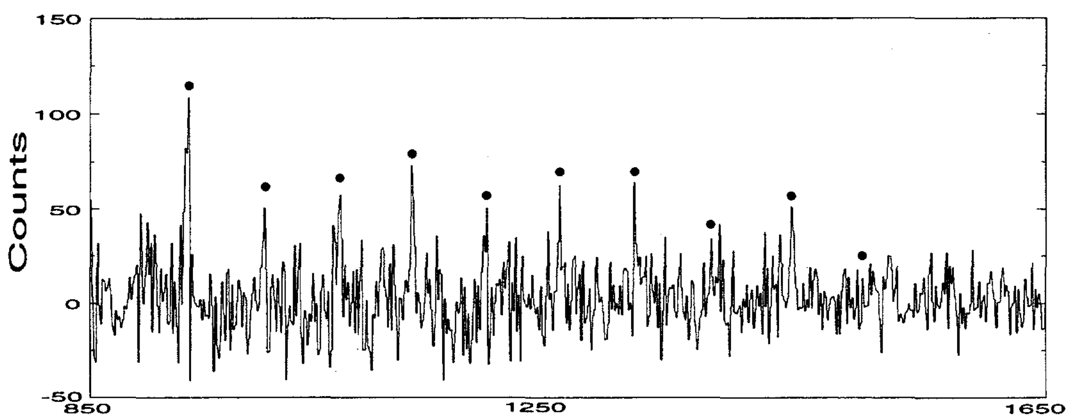

Fig. 2.8. The strongest of the three SD bands (members denoted by •) identified in one of the Pm isotopes. This spectrum was created by setting all unique combinations of doubles gates on all ten SD band members.

1. Lawrence Berkeley National Laboratory, Berkeley, CA.
2. Washington University, St. Louis, MO.
3. G. Hackman et al., *Phys. Rev. C* **52** (1995) R2293.
4. H.-Q. Jin et al., collected abstracts submitted to *Conference on Nuclear Structure at the Limits*, July 22–27, 1996, Argonne, Illinois, p. 19.

LOW–LYING LEVELS IN ^{140}Nd

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The light rare earth nuclei with $58 \leq Z \leq 62$ provide a unique laboratory for studying the transition from highly deformed to spherical shell model nuclei. The low–lying excitations of very neutron–deficient Nd isotopes, such as ^{130}Nd, are rotational bands built on well–deformed ground states.[4] Approaching the N = 82 shell closure, however, the well–defined rotational structures disappear and are replaced with single–particle excitations characteristic of spherical shell model nuclei.[4] We have studied the low–lying nuclear structure of the N = 80 Nd isotone, ^{140}Nd.

The data used in this analysis was collected following the bombardment of a thin self–supporting ^{100}Mo target by a 205–MeV beam of ^{48}Ca using a 58–detector version of GAMMASPHERE and the 95–element MICROBALL charged–particle detection array. This experiment was designed to search for hyperdeformation in the heavier Sm isotopes. Therefore, events were written to tape only when four or more Compton-suppressed Ge detectors fired in coincidence. During this run slightly fewer than 2.5 x 10^9 events were recorded. Approximately 10% of all events arose from the γ–ray deexcitation of Nd isotopes, as determined by coincidence with an α particle.

Our analysis has more than doubled the number of levels and transitions assigned to ^{140}Nd (see Fig. 2.9). Near N = 82 the major structure changes in ^{140}Nd are due to changes in the underlying neutron configurations. The lowest–lying excitations in ^{140}Nd are dominated by the two–neutron hole configurations $\nu\{h_{11/2}^{-1}d_{3/2}^{-1}\}_{7-}$ and $\nu\{h_{11/2}^{-2}\}_{10+}$ as noted in Ref. 2. In Ref. 2, two of the highest–lying levels have been tentatively assigned with spins of (15) and (16). From our work we can tentatively assign this 16^- level to the four neutron–hole $\nu\{h_{11/2}^{3}d_{3/2}^{-1}\}_{16-}$ configuration.

ORNL-DWG 97-5501

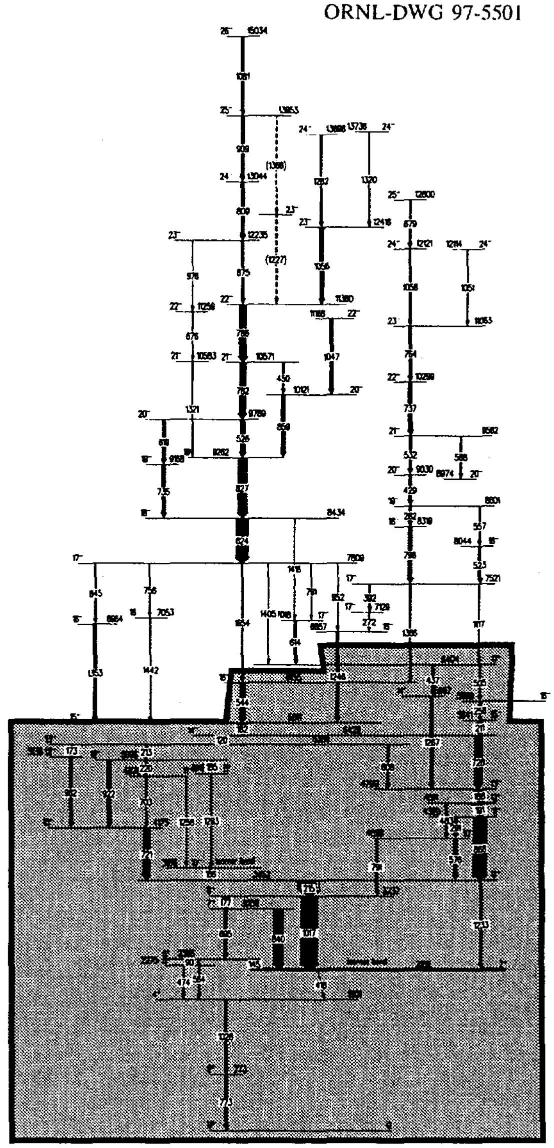

Fig. 2.9. The low–lying level scheme of ^{140}Nd determined in this work. The shaded area is the portion of the level scheme that was previously known.[4]

1. Diplom student from the Royal Institute of Technology, Stockholm, Sweden.
2. Lawrence Berkeley National Laboratory, Berkeley, CA.
3. Washington University, St. Louis, MO.
4. E. Gülmez, H. Li, and J. A. Cizewski, *Phys. Rev.* C **36** (1987) 2371, and reference therein.

MULTIPLE SUPERDEFORMED BANDS IN Sm ISOTOPES: TRANSITION FROM LARGE DEFORMATION TO SUPERDEFORMATION

H.-Q. Jin,[1] C. Baktash, M. J. Brinkman, D. Rudolph, C.-H. Yu, R. M. Clark,[2] M. Devlin,[3] P. Fallon,[2] D. R. LaFosse,[3] I. Y. Lee,[2] F. Lerma,[3] A. O. Macchiavelli,[2] and D. G. Sarantites[3]

Heavy Sm nuclei fall in an interesting region which bridges the island of large-deformation nuclei (A ~ 130) on one hand, and superdeformed (SD) nuclei (A > 140) on the other. Therefore, they are expected to provide insight into the question of evolution of deformation from axis ratios of about 3:2 in the lighter nuclei to ~ 2:1 in the heavier systems. So far, however, in this mass region only two SD bands have been reported in ^{142}Sm.[4] The properties of these two bands support the presence of a SD neutron shell gap at N = 80.[5]

Here we report results of superdeformation studies in ^{142,143,144}Sm nuclei. The experiment was performed at the LBNL 88" cyclotron using the ^{100}Mo(^{48}Ca,*xn*) reaction at a beam energy of 205 MeV. About 15% of the products of this reaction involved emission of charged particles (protons and alphas), which were cleanly separated using the MICROBALL, a 4π array of CsI charged-particle detectors. Gamma rays were detected using 57 Ge detectors of the GAMMASPHERE. A total of 2 x 10^9 four-fold and higher γ-correlated events were recorded. Analysis of the γ-γ-γ cubes created for the *xn* channels revealed at least eight rotational bands with γ-ray energy spacings of ~ 60 keV, characteristic of the SD bands in this region. On the basis of the known γ transitions between the low-lying states, three of these bands were tentatively assigned to ^{143}Sm and four to ^{144}Sm. The latter set constitutes the first observation of high-spin SD bands in a stable nucleus. We also observed the known yrast SD band[4] in ^{142}Sm, but the reported excited band in this nucleus could not be identified, mainly due to the close similarity of the transition energies in this band to those in the yrast SD band of ^{144}Sm.

The $\Im^{(2)}$ moments of inertia of these bands are plotted as a function of rotational frequency in Fig. 2.10. They generally fall in the range of 60-70 $\hbar^2$MeV^{-1}, intermediate between the $\Im^{(2)}$ values of the large-deformation bands in the A ~ 130 region, and the SD bands in the heavier Gd isotopes. One of the bands in each of the ^{143}Sm and ^{144}Sm nuclei show a low-frequency crossing at $\hbar\omega$ ~ 0.5 MeV, which is similar to the crossing observed in ^{144}Gd.[6] A second band in ^{143}Sm (triangles) shows a sharp crossing at $\hbar\omega \simeq 0.7$ MeV. Both of these crossings may be attributed to the $\nu 7_1$ neutron crossings.

ORNL-DWG 97-5427

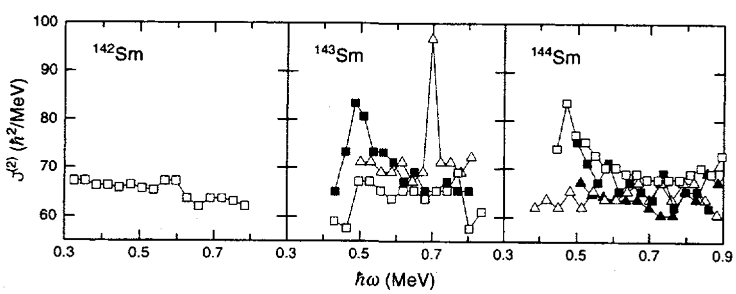

Fig. 2.10. Dynamic moments of inertia, $\Im^{(2)}$, as a function of rotational frequency for the eight observed SD bands in ^{142,143,144} Sm.

1. University of Tennessee, Knoxville.
2. Lawrence Berkeley National Laboratory, Berkeley, CA.
3. Washington University, St. Louis, MO.
4. G. Hackman et al., *Phys. Rev. C* **52**, R2293 (1995).
5. S. M. Mullins et al., *Phys. Rev. Lett.* **66**, 1677 (1991).
6. S. Lunardi et al., *Phys. Rev. Lett.* **72**, 1427 (1994).

STUDY OF HIGH-SPIN STATES IN ODD-ODD ^{158}Ho

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High-spin states of ^{158}Ho were populated using the ^{150}Nd(^{14}N, 6n) reaction at a beam energy of 92 MeV. Gamma rays were detected by the 36-Ge detectors of Phase I of the GAMMASPHERE array. About 1 billion triple- or higher-fold coincidence events were collected in the experiment. The preliminary results have established nine rotational bands in ^{158}Ho.

In a comparison of the AB neutron band crossing frequency of ^{158}Ho with its neighboring odd-N, even-Z and even-even nuclei, we found that ^{158}Ho lacks the so-called "blocking effect" that is expected in an odd-odd nucleus. Figure 2.11 shows that the band crossing frequencies for the odd-N, even-Z nuclei (triangles) are systematically reduced compared with those for the even-even nuclei (circles). This has been understood as the result of the reduced neutron pairing correlations in the odd-N nuclei due to the blocking effect of the odd neutron. However, the blocking effect does not exist in most odd-odd nuclei. Except for ^{164}Tm, the band crossing frequencies for all the odd-odd nuclei shown are nearly the same as or even larger than those for their even-even neighbors. Cranked shell model calculations show that the deformation difference cannot account for the much higher $\hbar\omega_c$'s for the odd-odd nuclei, see Fig. 2.12. The abnormally large AB neutron band crossing frequencies in these odd-odd nuclei are extremely difficult to understand in terms of the current theoretical models. It is possible that the failure of theoretical calculations is due to the lack of a coherent treatment of neutron-proton residual interactions.

ORNL-DWG 97-5439

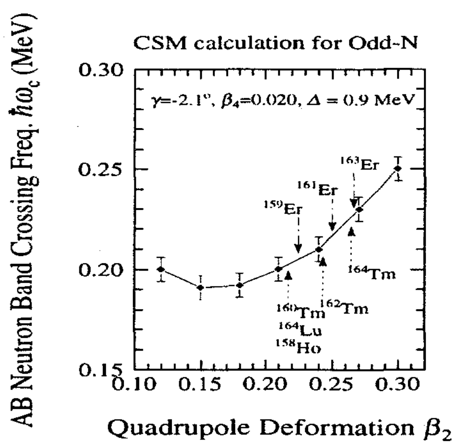

Fig. 2.11. CSM calculations of AB neutron crossing frequencies as a function of β_2. TRS predicted β_2's for nuclei of interest are indicated with arrows.

ORNL-DWG 97-5440

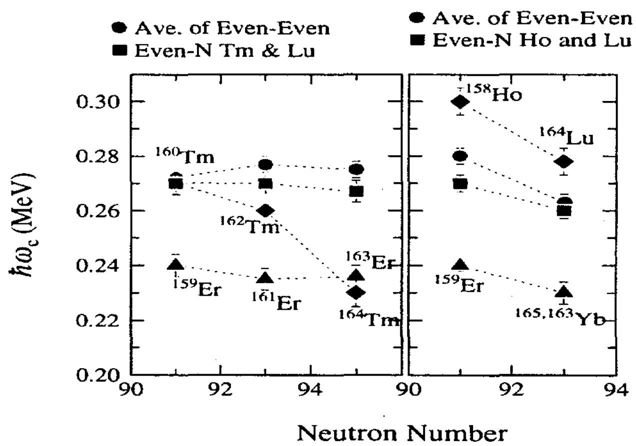

Fig. 2.12. Summary of AB neutron band crossing frequencies for odd-odd ^{160,162,164}Tm (left panel) and ^{158}Ho, ^{164}Lu (right panel) in comparison with the averaged values of their neighboring even-even nuclei as well as those of their neighboring odd-A nuclei.

1. University of Rochester, Rochester, NY.
2. Chalk River Laboratories, Chalk River, Ontario, Canada.
3. Lawrence Berkeley National Laboratory, Berkeley, CA.

THE ITERATED CORE

AN AUTOMATIC BACKGROUND SUBTRACTION ALGORITHM FOR HPGe COINCIDENCE DATA

M. J. Brinkman

Large multi–detector arrays of high–purity germanium crystals (HPGe) have provided a wealth of γ–ray spectroscopic information and revolutionized the study of high–spin nuclear states. In order to accurately determine the transitions in coincidence with a given peak and their intensities, however, it is necessary to subtract background counts from both Compton–scattered and quasicontinuum γ rays associated both with the peak of interest and large peaks found in the matrix.

The traditional method of subtracting background from spectra involves setting gates on the channel of interest and nearby background channels and subtracting the latter from the former. There are four disadvantages inherent in this method.

1) It is highly subjective, as it is difficult to find nearby background channels free from weak contaminants.
2) It is difficult to automate this procedure to subtract a large number of spectra.
3) It unnecessarily increases the statistical uncertainties of the background subtracted spectrum.
4) Correlated background remains unsubtracted using this technique.

A possible solution to these problems was put forward by Andersen and coworkers[1] with the description of the Copenhagen COR method, an objective and fully automatic background subtraction procedure.

The Copenhagen COR starts with the assumption that all background events in a matrix are completely uncorrelated. Unfortunately, counts arising in the matrix from γ–γ photopeak events are highly correlated, and, thus, are oversubtracted everywhere throughout the matrix. By iterating over the matrix prior to background subtraction one can provide suitable estimates for the parameters used in the Copenhagen COR. This extension is called the Iterated Core, and it removes the oversubtraction problems inherent in the original Copenhagen COR.

ORNL-DWG 97-5444

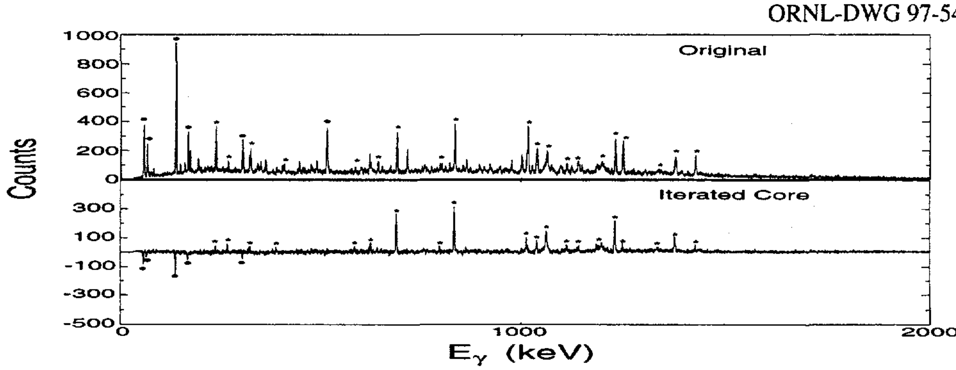

Fig. 2.13. Spectra created by setting a gate on a transition populated following the bombardment of a 70–MeV beam of ^{16}O on a ^{58}Ni target collected using the Florida State/Notre Dame/Pittsburgh spectrometer. In these spectra the * (•) denote transitions in known coincidence (uncorrelated) with the gate. Top: The gate described above before any background subtraction. Bottom: The same spectrum following the application of the Iterated Core.

1. O. Andersen, J. D. Garrett, G. B. Hagemann, B. Herskind, D. L. Hillis, and L. L. Riedinger, *Phys. Rev. Lett.* **43**, 687 (1979).

AUTOMATIC GERMANIUM CALIBRATION SYSTEM FOR HRIBF

M. J. Brinkman

The nuclear structure experimental end station will include a large number of channels of high–purity germanium (Ge) data. As originally proposed[1] 98 channels will need to be instrumented. As part of our ongoing user interface development work, we have developed, implemented, and tested a method for automatically calibrating these signals and to interactively enter these corrections into the on–line sorting. The algorithm used is an extended modification of a similar method developed by T. Lauritsen of Argonne National Laboratory for use at GAMMASPHERE.[2]

Calibrating the on–line signals requires gathering spectra for each of the independent Ge crystals. Following this collection procedure, we subtract the underlying background for each spectrum. We begin by logarithmically smoothing the raw spectra, using a parabolic filter with the appropriate width. Following this, we iteratively generate an overdamped spectrum from the smoothed data for use as a background spectrum. Finally, the generated background spectrum is subtracted from the smoothed data creating a "peak" spectrum.

To calibrate the detectors, a maximum likelihood approach is undertaken to match peak spectra to a reference spectrum. Our algorithm defines the quality function to be the sum of the overlap of the two spectra (i.e., the peak spectra are multiplied by the reference spectrum channel by channel and the resulting values are summed to provide a figure of merit). We then undertake a multi–dimensional simplex optimization to find the maximal value of the quality function with respect to correlated values for the calibration parameters. To test this procedure, we have used data collected using an 82–detector implementation of GAMMASPHERE. In our tests we used both linear and quadratic calibrations and found that the simple linear calibration provided acceptable accuracy. We were able to determine the optimal calibrations for 82 detectors in slightly less than 10 minutes of total computational time.

As a separate project, we have developed a package to provide a method for changing sorting parameters in SCANU[3] on line without necessitating recompilation of the user scanning subroutine. This package, OLGA (for On–Line GAting), consists of two parts—the first a subroutine library that is embedded in customized SCANU processes and the second an application that runs under a separate process. The application communicates with the embedded OLGA subroutine via shared memory. In an effort to provide maximum flexibility, the OLGA application is a customized version of a Tcl[4] shell, which provides variable substitution, command creation, and looping and control functionality. As part of our testing procedure, we have written a few simple procedures that allows users to change the on–line calibration of Ge detectors using calibration commands similar to those found in DAMM.[5]

The only remaining task that needs to be undertaken to fully implement on–line Ge calibration capability is to provide procedures that connect the core computational system with the OLGA interface. Although not tested, this extension can be achieved trivially through standard file I/O.

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1. *Oak Ridge National Laboratory γ–Ray Detection Array Upgrade for Radioactive Ion Beam Physics Using the Recoil Mass Spectrometer*, M. J. Brinkman editor, a proposal to the U.S. Department of Energy, December 1994.

2. T. Lauritsen, *From the Front End to the Final Spectrum*, a two–part presentation at the *Workshop on Data Analysis*, February 7–10, 1996, Oak Ridge, TN.

3. W. T. Milner, *scanu—User Customized Histogramming*, ORPH UBOOK, May 1996.

4. J. Ousterhout, *Tcl and the Tk Toolkit*, Addison–Wesley Publishing Company, 1994.

5. W. T. Milner, *DAMM*, ORPH UBOOK, May 1996.

SIMULATING CLOVER DETECTORS
Summary of a Student Research Project[1]

H. D. Sanders[2] and M. J. Brinkman

The nuclear structure end station and its upgraded γ–ray detection array[3] will be one of the major experimental instruments for undertaking RIB–based experimental work. Optimizing the performance of this array requires maximizing photopeak detection efficiency while retaining acceptable energy resolution and peak–to–total values. Simulations of the germanium detectors comprising the array provide a means of maximizing its performance.

The dual goals of maximizing energy resolution and absolute efficiency are in competition with each other. Increasing the size of a Ge detector or decreasing its distance to the source of γ radiation increase the absolute efficiency. This increase, however, comes at the cost of a concomitant decrease in energy resolution for experiments involving a moving source such as those typical from the deexcitation of recoiling nuclei populated via heavy–ion fusion–evaporation reactions.

By shaping four 25% Ge detectors (25% photopeak efficiency compared to a 3" x 3" cube of NaI for 1332–keV γ rays) and arranging them into a "clover leaf" pattern, one can obtain an absolute photopeak efficiency equivalent to a larger detector. Determining which of the four crystals received the first "hit" from the incident γ ray, one retains the smaller angular resolution of the 25% detector and improves the energy resolution for γ rays arising from moving sources. Recently, it has become possible to further segment a "Clover" detector by breaking the outer electrodes, providing a further improvement in measuring the position of the first hit. We have undertaken Monte–Carlo simulations of a segmented Clover detector to determine the expected improvement in energy resolution that can be obtained. Sample results are presented in Fig. 2.14, below.

ORNL-DWG 97-5445

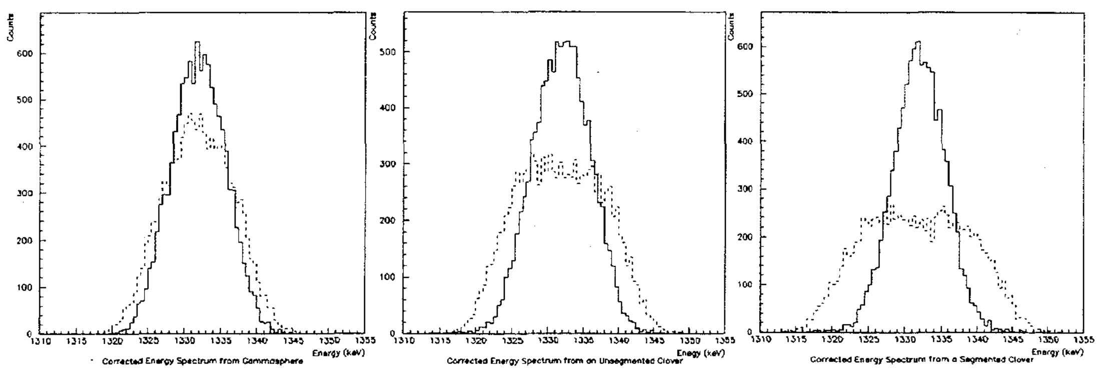

Fig. 2.14. Simulations of a segmented, large–volume (75%) single crystal Ge detector, a standard Clover, and one of the new segmented Clovers, from left to right, respectively. In each of these simulations the dashed line corresponds to data from a 1332–keV γ ray emitted from a source traveling at 5% of c, while the solid line corresponds to the same data after the application of a Doppler correction. The segmented Clover was positioned 15 cm from the moving source, while the other two detectors were placed 20 cm from the same source.

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1. H. D. Sanders, *Simulating a Clover Detector Using Geant 3.21,* ORNL internal report from the Science and Engineering Research Semester Program, December 1995.

2. Science and Engineering Research Semester Student from Cornell University.

3. *Oak Ridge National Laboratory γ–Ray Detection Array Upgrade for Radioactive Ion Beams Studies Using the Recoil Mass Spectrometer,* M. J. Brinkman, editor, a proposal to the U.S. Department of Energy, December 1994.

NUCLEAR REACTIONS

PHOTON DECAYS FOLLOWING THE PROJECTILE EXCITATION OF ^{11}Be

N. Gan,[1] J. R. Beene, M. L. Halbert, D. W. Stracener,[1] R. L. Varner
A. Azhari,[2] E. Ramakrishnan,[2] P. Thirolf,[2] M. Thoennessen,[2] and S. Yokoyama[2]

Recently, considerable interest has arisen in the study of the light neutron-rich nuclei such as ^{11}Be using intermediate energy radioactive beams.[3,4] We are beginning a program of measurements of the giant dipole resonance strength distribution in exotic nuclei, using the method of virtual photon scattering. We conducted experiment 94021 at the National Superconducting Cyclotron Laboratory at Michigan State University to measure the GDR strength distribution in ^{11}Be. The ^{11}Be was in a 77–MeV/u beam of 10^6 particles per second, produced by the A1200 facility. Coulomb collisions with an 80–mg/cm^2–thick Pb target produced the virtual photon flux. We measured coincidences between the γ rays and the forward–scattered, projectile–like particles. The projectile–like particles were detected with the zero–degree detectors of the MSU 4–π array covering a polar angle range of 1.10° – 3.24°. The photons were measured with the 142-element ORNL–TAMU–MSU BaF_2 Joint Array in the polar angle range of 12° – 45°.

In Fig. 2.15, the γ-ray spectra gated on the ^{11}Be and ^{10}Be particles are shown. The 320-keV peak, which is the only discrete E1 transition ($1/2^- \rightarrow 1/2^+$) of the ^{11}Be nucleus, is clearly seen. After correcting for detector efficiencies and normalizing to elastic scattering, we obtain a cross section of 23 mb in the angle acceptance of the particle detector. The result is significantly lower than the 89-mb value expected from a calculation using the measured B(E1) = 0.116e^{2}fm.^{2} We do not yet understand this discrepancy.

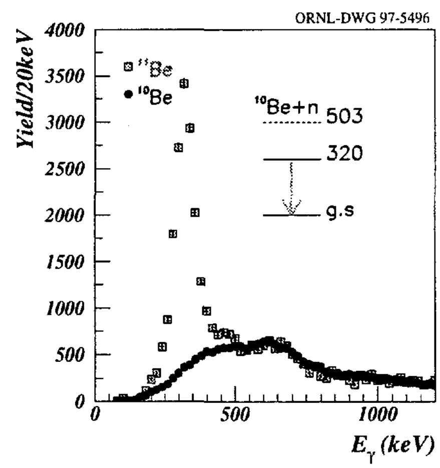

Fig. 2.15. γ–ray spectra of the ^{11}Be and ^{10}Be nuclei. Doppler shifts are corrected in energy.

Between the neutron separation energies of ^{11}Be (0.503 MeV) and ^{10}Be (6.813 MeV), photon emissions are dominated by the daughter nucleus ^{10}Be. Since it is difficult to directly extract the ^{11}Be photons from the γ-ray spectra, we have fitted the particle energy spectra gated by different photon energy bins and used the area of the ^{11}Be peak as the photon yield. Although we still see contaminations from the photon decays of the 3-MeV and 6-MeV states in ^{10}Be, it is possible to separate the ^{11}Be and ^{10}Be components above the ^{10}Be neutron separation energies. We are currently refining our fitting procedure to obtain the E1 strength distribution. We will remeasure these data with a higher resolution particle detector array.

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1. ORNL Postdoctoral Associate, Oak Ridge Institute for Science and Education.
2. Michigan State University, East Lansing.
3. R. Anne, *Z. Phys. A* **352**, 397 (1995).
4. T. Nakamura, *Phys. Lett. B* **331,** 296 (1994).

STUDIES OF ^{208}Pb(p,p′γ) USING THE ORNL BaF_2 ARRAY WITH E_p = 200 MEV

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This experiment, E360 at the Indiana University Cyclotron Facility, was designed to investigate the excitation of the isovector giant dipole resonance (GDR) by the strong nuclear interaction and to determine the shape and strength of the GDR transition potential. The motivation and experimental details were described earlier.[5]

In this experiment the GDR was isolated by gating on its ground-state photon decay. This technique provides a "clean" GDR spectrum because the GDR has a much stronger branch to the ground state than any other giant resonance in the same excitation energy region. The direct observation of the GDR in hadronic excitation permits us to study the isovector potential strength, which is difficult to observe unambiguously in any nuclear reaction, and the GDR transition strength distribution, which has previously only been inferred indirectly.

To implement the technique, we histogram the particle energy, observed in the IUCF K600 spectrometer, and the photon energy observed in our BaF_2 detectors. Then we extract a particle energy spectrum from the events in which the target nucleus emits only one photon having an energy equal to the nuclear excitation energy. These ground-state decays are then histogrammed as in Fig. 2.16(a). In the bound-state region, we observe the low-lying collective states, as well as several dipole states up to the neutron separation energy, 7.4 MeV. There are a significant number of counts in the GDR region, which we will further analyze, including the mapping of the angular distributions of the photons. The dipole states in the bound-state region are of interest, and we will study them as well. Also of interest are decays to bound states such as the 2.61 MeV 3^- state, shown in Fig. 2.16(b), which might indicate isovector strength in the GQR region.

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1. Partial support provided by Vanderbilt University and Oak Ridge Associated Universities under the Laboratory Graduate Research Program.
2. Vanderbilt University, Nashville, TN.
3. Indiana University Cyclotron Facility, Bloomington.
4. Michigan State University, East Lansing.
5. D. H. Olive et al., *ORNL Physics Division Progress Report*, ORNL-6842, (1994).

ORNL-DWG 97-5529

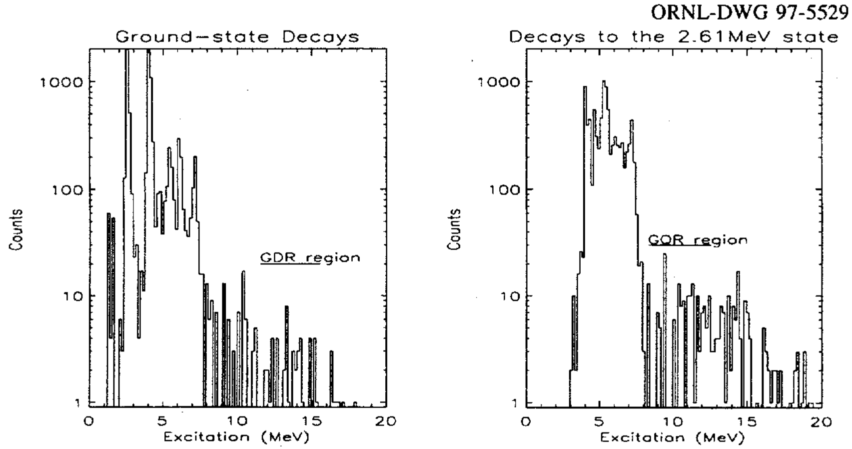

Fig. 2.16. (a) The spectrum of ground state decays, binned in 0.160 MeV bins. The yield above 7.4 MeV corresponds to decays from the continuum. (b) The spectrum of one photon decays through the 3^- (2.61 MeV) state.

EXCITATION FUNCTIONS FOR GDR γ RAYS IN COINCIDENCE WITH FISSION FOR THE ^{32}S + ^{NAT}W, ^{208}Pb REACTIONS

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J. R. Beene, N. Gan, M. L. Halbert, D. W. Stracener, R. L. Varner,
M. Thoennessen,[2] and I. Dioszegi[3]

High energy γ–rays from the decay of the giant dipole resonance (GDR) built upon excited states were measured in coincidence with fission for the ^{32}S + ^{nat}W, ^{208}Pb reactions. The experiments were performed in order to extend the existing excitation functions,[4,5] and to observe the competition of the pre-scission GDR γ emission with fission at higher excitation energies.

The GDR γ rays were detected in the ORNL-MSU-TAMU array, which consists of 154 BaF_2 crystals, with a total solid angle of ≈ 0.4 π sr. The array was positioned at 90° to the beam axis at a distance of 54 cm from the target, allowing good γ–ray and prompt neutron separation. Pile-up rejection was performed using the ratio of the total to fast light output from the BaF_2 scintillators. Fission fragments were detected in position-sensitive parallel plate avalanche counters, and identified by their energy loss and time-of-flight with respect to the pulsed Stony Brook LINAC beam.

The fission γ-ray anisotropy,[6] defined by the ratio $W(\theta = 0°, E_\gamma)/W(\theta = 90°, E_\gamma)$, was also measured. Here, θ is the angle between the compound nucleus spin axis and the direction of the emitted γ ray. This quantity reveals information about the deformation of the fissioning system. For an axial symmetric prolate deformed nucleus, the GDR strength function splits into vibrations parallel and perpendicular to the nuclear symmetry axis. Thus, the GR has a low–energy component (for the parallel vibration) and a high–energy component (for perpendicular vibrations), where the latter has twice the sum-rule strength of the former for a prolate deformed nucleus.

The GDR γ-ray multiplicities are plotted in Fig. 2.17(a) for the ^{32}S + ^{nat}W reaction, for excitation energies in the range 67–120 MeV. In part (b) of the figure, $W(0°,E_\gamma)/W(90°E_\gamma)$ is plotted for energies corresponding to those in Fig. 2.17(a). The anisotropy in the region of the compound nucleus GDR, $E_\gamma \approx 11$ MeV, is more pronounced at the higher excitation energies.

Analysis for the ^{32}S + ^{208}Pb is proceeding. The deduced pre-scission GDR γ-ray multiplicities and the fission fragment γ-ray anisotropies will be compared to calculations from a statistical model, modified to include the effects of nuclear dissipation.

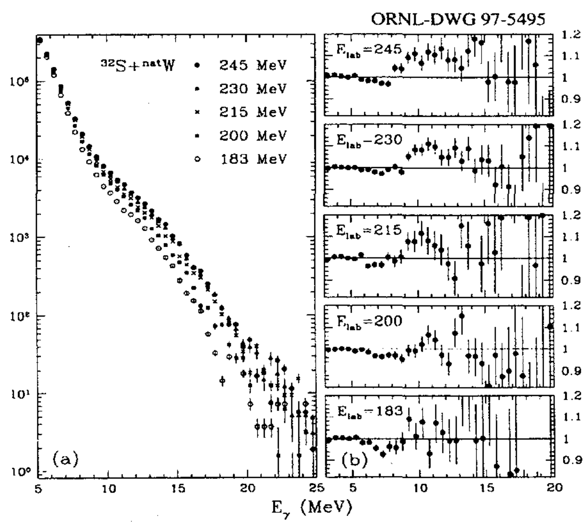

Fig. 2.17. The relative γ-ray multiplicity for the 5 excitation energies. Each spectrum has been normalized to the 230 MeV spectrum at Eγ = 4.75 MeV (b) The fission γ-ray anisotropy.

1. University of New York at Stony Brook, Stony Brook.
2. Michigan State University, East Lansing.
3. Institute of Isotopes, Hungarian Academy of Sciences, H-1525, Budapest, Hungary.

4. R. Butsch, D. J. Hofman, C. P. Montoya, and P. Paul, *Phys. Rev. C* **44**, 1515 (1991).
5. I. Diószegi, D. J. Hofman, C. P. Montoya, S. Schadmand, and P. Paul, *Phys. Rev. C* **46**, 627 (1992).
6. R. Butsch, M. Thoennessen, D. R. Chakrabarty, M. G. Herman, and P. Paul, *Phys. Rev. C* **41**, 1530 (1990).

BaF_2 ARRAY DEVELOPMENT AND OPERATION

R. L. Varner, N. Gan,[1] J. R. Beene, D. W. Stracener,[1] M. L. Halbert,
J. L. Blankenship, K. L. Wolf,[2] and M. R. Thoennessen[3]

The ORNL BaF_2 array[4] has been joined with detectors and electronics from Texas A&M University (TAMU) and the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) to create the TAMU-ORNL-MSU joint array. The array is a complete instrument for detection of photons from 0.25 MeV to 100 MeV and higher, and is designed to operate alone or in coincidence with particle detectors of various kinds. It is composed of about 150 BaF_2 detectors with phototubes, electronics for signal processing and triggering, and a data acquisition system developed at the HRIBF facility at ORNL.

At present, the array is shared between the contributing institutions, roughly in proportion to the contributions of each: ORNL-21 weeks, TAMU-13 weeks, MSU-6 weeks. Twelve weeks are reserved for development and transportation. The array can be used at any facility by a member of the collaboration, but will be used predominately at the TAMU Cyclotron Laboratory and the NSCL at MSU.

The first experiment with the array was performed at NSCL, in April 1995, to measure virtual photon scattering from the radioactive nucleus ^{11}Be (N. Gan et al., this report). For this experiment, a new arrangement of the detectors was developed, the forward wall. This arrangement is specifically designed for decay studies of radioactive beams, in which the reaction products are forward-focused. This was also the first on-line test of our FASTBUS readout of the TDCs for the detectors. We use a system similar to HILI[5] for this, reading LeCroy 1872/1875 TDCs with an LRS 1821 FASTBUS Segment manager, transferring the data to an LRS 1131 SIB to VME interface. The TDC readout operated flawlessly up to the end of the experiment, when a fuse failed on one TDC, stopping our calibration.

From this first experience, we learned about the difficulties of bringing together the diverse equipment of the three labs and have taken steps to improve the instrumentation of the system. The largest problem was in matching the lengths of the signal and logic cables in the array, as well as matching the 500 nsec delays in the linear signals necessary for trigger formation with large, slow particle detectors. We constructed additional linear delay boxes, modeled after the units already in use by ORNL, as well as ECL delay modules, enough to instrument the detectors from TAMU and NSCL. In the course of this construction, the design of the ECL delay module was enhanced substantially, to reduce the power consumption and improve the output drive. The linear delay box, which incorporates a splitter/attenuator, was modified to provide an adjustable attentuation, to better match the logic signal pulse height to the discrimination for different full-scale photon energy ranges recorded in the ADCs. A final detail was that we remounted the electronics into deep racks, which simplifies transport and setting up of the array after each move.

Since that first experiment, the array has been used for three experiments at SUNY-Stony Brook, among which was Morton et al., c.f. this report, and Texas A&M for one experiment by Schmitt, Botting, Wolf et al., to investigate the fission time scale in several compound nuclei excited by different entrance channels.

The next series of experiments for the array will commence in November 1996, at the NSCL.

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1. ORNL Postdoctoral Associate, Oak Ridge Institute for Science and Education.
2. Texas A&M University, College Station.
3. Michigan State University, East Lansing.
4. J. R. Beene et al., *Physics Division Progress Report*, ORNL-6842 (1994), pp. 2-29.
5. J. W. McConnell et al., *Physics Division Progress Report*, ORNL-6746 (1992), p. 15.

UPGRADE OF THE PHOTOMULTIPLIERS FOR THE ORNL BaF_2 ARRAY

N. Gan,[1] D. W. Stracener,[1] J. R. Beene, M. L. Halbert, D. Shapira, and R. L. Varner

The ORNL BaF_2 Array has been in operation for seven years. Most of the photomultipliers[2] show signs of aging. Most of the degradation in the resolution has come from "afterpulsing" in which gas has diffused into the tube and sputters the photocathode in time. The degradation is sufficiently bad that we are now replacing our original photomultipliers.

We have evaluated several vendors' 2–inch quartz–window photomultipliers. Specifically, we have tested the R2059 from Hamamatsu Photonics, the XP2020Q from Philips Components, and the 9214QA from THORN EMI. We found that while the performance of the XP2020Q and the R2059 are similar, the 9214QA is inferior for both time resolution and energy resolution.

Based on this test and the best price, we have purchased 55 XP2020/Q04 photomultipliers from Philips Component. Forty of them have been tested. The average energy resolution for 662–keV γ ray from ^{137}Cs is 11.64%. The average peak-to-valley ratio for the 1.33–MeV γ ray from ^{60}Co is 1.88. The average time resolution is 355 ps. The average counting rate stability, which measures the change of the gain with counting rates from 1000 cps to 10000 cps, is 1.8%. The long–term stability, which is the gain-shift over 24 hours, is 1.3%. The distributions of energy resolution and time resolution are shown in Fig. 2.18.

Thirty–seven of the new photomultipliers have been incorporated into the array. The average energy resolution of the replaced detectors has been improved from 18.7% to 11.7%.

1. ORNL Postdoctoral Associate, Oak Ridge Institute for Science and Education.
2. Hamamatsu photomultiplier R2059.

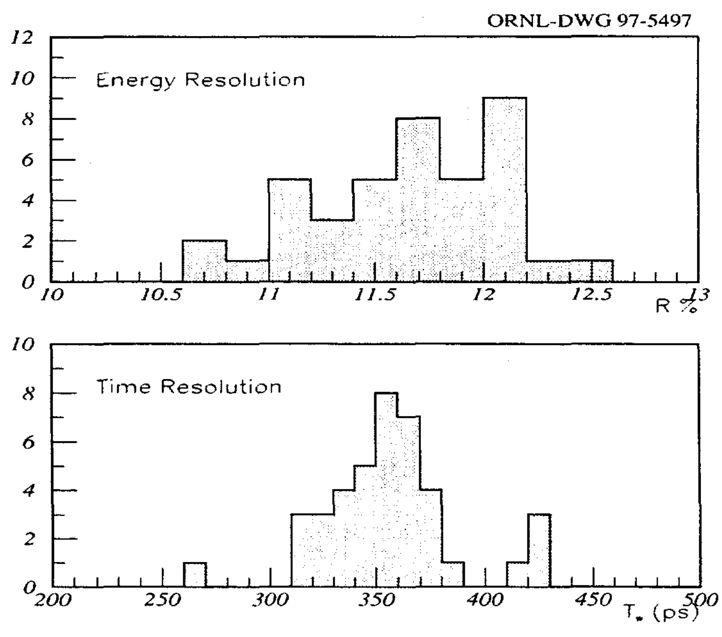

Fig. 2.18. The distributions of the energy resolution and time resolution of the XP2020/Q04 photomultipliers.

THE DESIGN OF A FORWARD PHOSWICH CHARGED-PARTICLE ARRAY

N. Gan,[1] J. R. Beene, M. L. Halbert, D. Shapira, D. W. Stracener,[1] and R. L. Varner

Study of photon decay following the projectile excitation in intermediate energy heavy-ion reactions usually requires measurement of the γ rays coincident with the projectile-like particles at forward angles. The low intensities of radioactive ion beams ($\approx 10^6$ /sec) make it feasible to directly detect the projectiles at very forward angles. We plan to construct a phoswich, charged–particle array, which will be used in conjunction with the ORNL-MSU-TAMU BaF_2 array to measure the GDR strength in radioactive nuclei, such as ^{11}Be and ^{17}Ne.

The whole array will contain 36 phoswich plastic detectors arranged in three concentric rings of 12 elements. It will be positioned 2 m from target and cover polar angles of 1° – 3.4° in the lab. (See Fig. 2.19). Each phoswich element will include a 2-mm-thick fast plastic ΔE detector with decay time constant of $\tau_d \approx 2$ ns, a 12-cm-deep slow plastic stopping detector $\tau_d \approx 200$ ns, a 7-cm-long Lucite-light guide, and a photomultiplier.

This highly segmented configuration was chosen to limit the counting rate to less than 1000 cps per element. The length of the E detector was chosen to stop 130 MeV protons. In order to obtain good Z identification, the thickness of the ΔE absorbs ≥ 0.03 of the total incident energy (Fig. 2.20). Meanwhile, the thresholds will be as low as 10 MeV/nucleon for H and He, 15 MeV/nucleon for ^{11}Be, 30 MeV/nucleon for ^{17}Ne, and 35 MeV/nucleon for ^{48}Ca. This array should be available for testing in January of 1997.

ORNL-DWG 97-5493

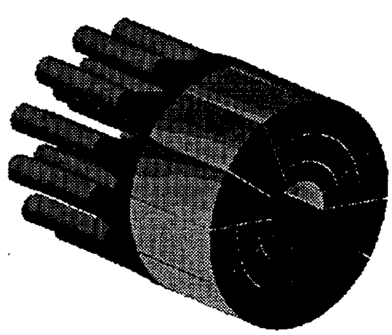

Fig. 2.19. The view of the forward phoswich detector array.

ORNL-DWG 97-5494

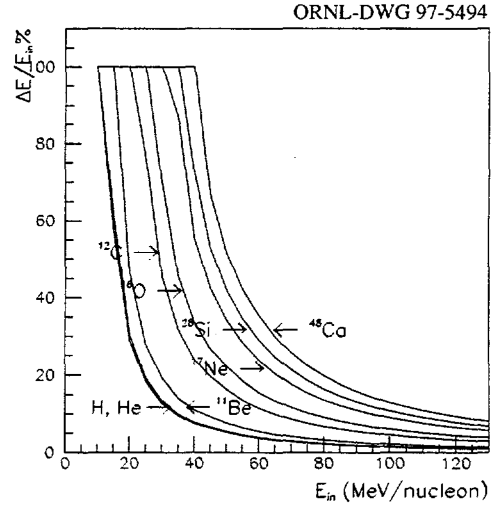

Fig. 2.20. The fraction of the energy loss in a 2 mm ΔE detector as a function of incident energy E.

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ADVANCED ELECTRONICS FOR THE BaF_2 ARRAY

R. L. Varner, J. L. Blankenship,[1] J. R. Beene, and R. A. Todd[2]

In the operation of the BaF array over the past few years, we have established several goals for the ideal electronics for the BaF_2 array. The main requirement is self-gated operation, in which each channel completes the processing of its analog signals without the need to wait for other detectors or slow coincidences with external detectors. Our present implementation in commercial electronics requires that we gate 16 to 64 channels with one gate, which requires that we delay the linear signals for 500 ns, as well as achieve time alignment good to 1 or 2 ns in each of the channels. We also desire that each channel have independently adjustable thresholds for the low energy (event detection) and the high energy (interesting event) discriminators, to allow for variation in gains for fast and slow light in the BaF_2 detectors. These, coupled with additional monitoring, scaling and testing features, as well as full automation, would make a module which significantly simplifies the electronics, increases the precision of the measurements and improves our reliability for all BaF_2 operations.

One approach to this problem is that of custom monolithic circuit design. We collaborated with RIS, Corp. in a DOE STTR ("Small business Technology Transfer and Research") grant, "Monolithic Circuits for Barium Fluoride Detectors used in Nuclear Physics Experiments"[3] to apply monolithic CMOS circuits designed for large detectors at CERN and RHIC to the problem of BaF_2. Much of the integrated circuit design for the high-energy physics community is directly applicable to intermediate energy heavy-ion and electron physics. This Phase I project was intended to develop a new integrated circuit chip-set by design, simulation, and testing of several prototype chips. These chips implemented basic function blocks, including charge-sensitive amplifiers, comparators, one-shots, time-to-amplitude converters and analog memory circuits. These chips were tested and reported to DOE. Regrettably, the Phase II project was not funded, despite generally good reviews of the project.

Another approach is to attempt to build such a device using commercially available components. We are now designing and constructing a test board using commercial comparators, a commercial charge-to-time converter[4] and other support circuits. This board will implement the two basic functions, self-gating and separate thresholds, in a NIM module. It will have one input for the BaF_2 signal, two discriminator outputs for the low energy and high energy discriminators, and outputs with pulses, the length of which are proportional to the integrated charge. The advantage of this module is (1) it gives us the custom features we need in circuits which are well-tested by someone else, and (2) it provides readout through standard computer interfaces we already support, e.g., the LeCroy 1877 FASTBUS TDC. However, it does not provide the very high circuit densities which CMOS provides. After implementation and testing of this board, we will investigate the costs and feasibility of implementing it on a larger scale, with fully automated controls.

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1. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
2. RIS Corporation, Oak Ridge, TN.
3. DE-FG05-95ER86029.
4 LeCroy Research Systems MQT200 and MQT300.

NUCLEAR COLLISION STUDIES WITH THE HILI DETECTOR ARRAY

D. Shapira, J. Gomez del Campo, J. W. McConnell, E. Chavez-Lomeli,[1]
H. Madani,[2] *J. Suro,*[2] *M. E. Ortiz,*[2] *and A. Dacal*[2]

Activity during the period covered by this report concentrated on three fronts:

1. Repeated attempts to run an experiment with beams that meet the required emittance and RF timing standard. Following attempts to introduce phase slits, it was determined that in order to obtain RF timing in the neighborhood of 1ns time resolution we had to use higher frequencies (second harmonic), reducing the time spread associated with a given phase acceptance.

2. During May 1995, a first successful run with 15 AMeV ^{84}Kr beam on ^{27}Al and ^{197}Au targets was completed. Running the cyclotron in second harmonic frequency (25 Mhz) allowed RF timing with 1.2 ns FWHM resolution enabling separation of protons, deutrons and tritons in the light particle yields detected in the hodoscope. A preliminary report on the results and first analysis of these data appeared in Ref.2.

3. Examination of Intermediate Mass Fragment (IMF) yields in this reaction[1] reveals some very interesting results. In order to have an accurate energy calibration for IMFs stopped in the plastic scintillator of the HILI light-particle scintillation hodosocope, we ran during November 1995, a calibration run at the Texas A&M Cyclotron Facility in which we used ^{12}C, ^{14}N, ^{16}O, and ^{40}Ar beams at several bombarding energies. Scattering from H, ^{12}C and ^{197}Au targets yielded several fiducials to test our semiempirical extrapolation of proton and alpha-particle calibration data to provide calibration for heavier fragments. The analysis of these data is complete now and a final report is in preparation. Figure 2.21 shows the results of such calibration data.

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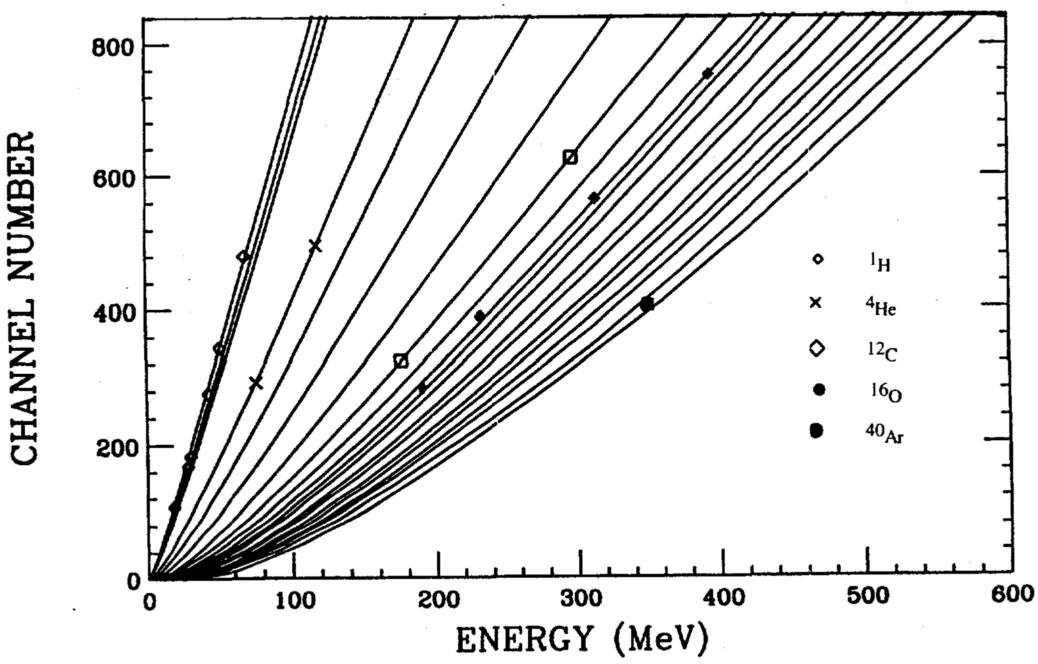

Fig. 2.21. Measured calibration data for several isotopes superposed on the curves from semiempirical calculations.

1. Instituto de Física, Universidad Nacional Autónoma de México, México.
2. H. Madani, E. Chavez-Lomeli, A. Dacal, M. E. Ortiz, J. Suro, J. Gomez del Campo, J. McConnell, and D. Shapira, *Revista Mexicana de Fisica* **42,** Suplemento 1, 188-197 (1996).

NUCLEAR ASTROPHYSICS

IMPROVED DETERMINATIONS OF *r*- AND *p*-PROCESS RESIDUAL ABUNDANCES FROM ORELA MEASUREMENTS OF CROSS SECTIONS FOR THE *s*-PROCESS

K. H. Guber,[1] P. E. Koehler, R. R. Spencer,[2] and R. R. Winters[3]

The measured solar system abundances reveal that there are three main mechanisms by which elements heavier than iron are synthesized in stars: the so-called *s*-, *r*-, and *p*-processes. Although the need for three separate processes as well as the gross features of each can be discerned from the pattern of the measured solar system abundances, understanding each process in more detail requires a deconvolution of these abundances.

Because the *s*-process is better understood than the *r*- and *p*-processes, the usual approach is to subtract the *s*-process abundances from the measured solar abundances to obtain the *r*- and *p*-process residual abundances. The *s*-process abundances are determined by fitting a stellar model to the few so-called "*s*-only" isotopes, which are shielded by stable isobars from the *r*-process and are thought to have negligible *p*-process contributions. In recent years, there have been substantial changes in *s*-process models as well as improvements in the input (n,γ) cross sections and abundance measurements. These developments may lead to substantial changes in the *r*- and *p*-process residual abundances. These abundances are the main constraints on models of these poorly understood nucleosynthesis mechanisms.

For example, the new *s*-process models predict this process to occur at a much lower temperature than the canonical classical *s*-process. Because many previous (n,γ) measurements were made with too high lower-energy cutoff to determine the astrophysically relevant Maxwellian averaged reaction rates at the new lower temperature, the "calibration" of these new models is uncertain. Hence, the *r*-process residual abundances determined using the new *s*-process models may undergo substantial changes if the reaction rates are affected significantly by resonances below the cutoff of the old (n,γ) measurements.

One *s*-only nuclide on which we have just completed measurements is ^{116}Sn. The classical as well as stellar models of the *s*-process substantially underpredict the abundance of ^{116}Sn relative to other *s*-only calibration points. One result of this is a decreased *r*-process residual abundance for masses just lighter than the mass A = 130 peak. It is in just this region, near A = 120, that *r*-process models consistently underpredict the observed abundances. There have been several suggested solutions to the inability of the *s*- and *r*-process models to reproduce the observed abundances in this mass region. However, all of these proposed solutions have a crucial dependence on the low-temperature ^{116}Sn(n,γ) reaction rate, which is uncertain because previous measurements do not extend low enough in energy. Our new data will fill this gap and may help resolve this long-standing problem. More measurements of this kind will help to improve supernovae models by providing constraints on conditions such as the neutron density, the temperature, and the duration of the *r*-process.

A second example of the impact of our recent measurements concerns the *p*-process abundance of ^{142}Nd. Previous measurements and analyses of the *s*-process nucleosynthesis of this isotope have indicated that about 15% of its solar abundance is due to the *p*-process. However, models of the *p*-process consistently yield a much lower abundance of about 5%. The solution to this problem may lie in the low-energy ^{142}Nd(n,γ) cross section which, until our recent measurements, was unreliable. Our data indicate that this cross section is much lower than previously thought. This results in a larger ^{142}Nd abundance from the *s*-process calculations, and hence a lower *p*-process residual abundance in agreement with current models. It is expected that future measurements of this type, coupled with the new improvements in *s*-process models, will allow more accurate determinations of the small *p*-process residual abundances. This will provide more constraints on this poorly understood mode of nucleosynthesis and on the stellar site(s) where it occurs.

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IMPROVING OUR UNDERSTANDING OF *p*-PROCESS NUCLEOSYNTHESIS BY MEASURING (n,α) CROSS SECTIONS

P. E. Koehler and Yu. P. Popov[1]

Although many different astrophysical sites have been proposed as the birthplace of the proton-rich isotopes of the intermediate and heavy elements (the so-called "*p*-nuclei"), many questions and uncertainties remain regarding their origin. At present it is thought that they were synthesized in an explosive environment via a series of (γ,n), (γ,α), (γ,p), and (n,γ) reactions starting from seed nuclei produced by the *s*-process. Alternatively, the lighter *p*-nuclei may have been produced in the *rp*-process.[2] However, the uncertainties in the rates for the reactions of interest are so large that it is currently not possible to associate these schematic models with any particular astrophysical site.

The rates with the largest uncertainties are those for (γ,α) reactions. Because many of the reactions in the *p*-process flow involve short-lived radioisotopes, direct measurements currently are possible only for a very few cases. Although the level density is high enough for nuclear statistical models to be applicable for calculating these rates, there is in general very poor agreement between the calculations and the limited experimental data.[3] The main problem with the calculations is thought to be that the alpha-nucleus potential is poorly known.

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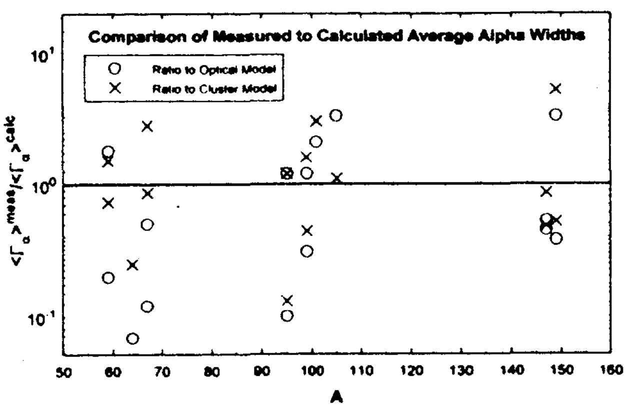

Fig. 2.22. Comparison of measured and calculated average alpha widths.

We propose to improve the statistical models, and hence the input "data" for the *p*-process calculations, by making measurements sensitive to the alpha-nucleus potential. The main idea is to use the (n,α) reaction to measure the alpha widths of many resonances for a number of nuclei. The result will be the average alpha width, $<\Gamma_\alpha>$, as a function of mass number, etc. These data will then be used to constrain the statistical model calculations of the (γ,α) cross sections needed for the *p*-process calculations. In Fig. 2.22, we compare the available data[4] to two different calculations. In contrast to statistical model calculations of (n,γ) cross sections, where the theory and experiment agree to within a factor of 2 for over 90% of the isotopes, there are on average much larger differences between the measured and calculated $<\Gamma_\alpha>$ values. These differences may be due in part to the fact that the experimental data are very limited - some of the measured $<\Gamma_\alpha>$ values are based on only two or three resonances. On the other hand, the measured $<\Gamma_\alpha>$ values for the Sm isotopes are based on 30 or more resonances and are still more than a factor of two different from the theoretical values.

We have used statistical model estimates of the cross sections and our previous $^{17}O(n,\alpha)$ measurements[5] at ORELA to estimate the feasibility of measurements of this type. Our survey indicates that measurements should be possible for as many as 30 nuclides between ^{32}S and ^{177}Hf.

1. Joint Institute for Nuclear Research, Dubna, Russia.
2. H. Schatz et al., submitted to *Nuclear Physics.*
3. E. Somorjai et al., submitted to *Nuclear Physics.*
4. A. Antonov et al., *Sov. J. Nucl. Phys.* **27**, 9 (1978).
5. P. E. Koehler, J. A. Harvey, and N. W. Hill, *Nucl. Instrum. Methods Phys. Res.* **A 361**, 270 (1995).

RESONANCE NEUTRON CAPTURE AND TRANSMISSION MEASUREMENTS AND THE STELLAR NEUTRON CAPTURE CROSS SECTIONS OF ^{116,120}Sn

P. E. Koehler, R. R. Spencer,[1] R. R. Winters,[2] and K. H. Guber[3]

We have made high-resolution (n,γ) and transmission measurements on isotopically enriched samples of ^{116}Sn and ^{120}Sn at the ORELA in the energy range from 100 eV to 500 keV. Improved astrophysical reaction rates for these isotopes are of interest because current nucleosynthesis models are not able to reproduce the observed abundances in this mass region. Although several other solutions have been suggested, it is possible that the problem lies in the (n,γ) cross sections used in the models. Previous (n,γ) measurements[4-7] had a lower energy limit of 3 keV or higher, which is too high to determine accurately the Maxwellian-averaged capture cross sections at the low temperatures (kT = 6 - 8 keV) favored by the most recent stellar models of the *s* process. Also, with our new transmission data we are able to calculate accurately the often substantial finite-thickness corrections to the (n,γ) data, and hence obtain more accurate astrophysical reaction rates than in previous work.

A small portion of our data for ^{116}Sn is shown in Fig. 2.23. We are currently extracting the resonance parameters and hence cross sections for the resolved resonance region from these data. In Table 2.1, we compare average cross sections from our initial analysis to the most recent previous work. The columns labeled "Wisshak *et al.* Numerical" and "Wisshak et al. Resonance" resulted from a numerical integration[4] and resonance analysis[5] of their data, respectively. Our results are given in the column labeled "ORELA." As can be seen, there are substantial differences between our results and those of Wisshak *et al.* Nearly all of these differences appear to be traceable to the lack of high-quality transmission data previous to our work. In addition, our analysis indicates that approximately 10% of the astrophysical reaction rate at 10 keV is due to resonances below the 3 keV cutoff of previous experiments.

We will extend our resonance analysis to higher energies and to ^{120}Sn. The result should be much more accurate astrophysical reaction rates for these isotopes than were previously available. Our new rates will be used in a reanalysis of the *s* process in the tin region in an attempt to reconcile previous inconsistencies between theory and experiment.

Table 2.1. Comparison of average cross sections

E (keV)	σ (mb) Wisshak et al. Numerical[4]	Wisshak et al. Resonance[5]	ORELA
3-5	205.0±17	297.5±12.8	242.9±7.3
5-7.5	293.5±8.5	254.6±9.5	303.9±9.1
7.5-10	168.7±5.1	152.4±5.3	158.0±4.7
10-12.5	156.5±3.4	143.3±7.4	156.0±4.7
12.5-15	156.7±2.8	146.6±3.5	159.4±4.8
15-20	138.2±1.5	133.1±1.8	141.5±4.2

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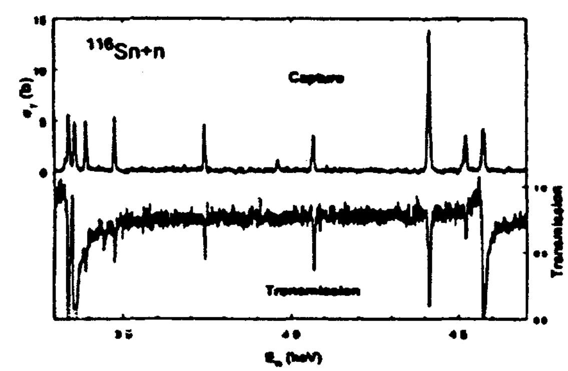

Fig. 2.23. Example capture (top) and transmission (bottom) data from our ORELA measurements on ^{116}Sn.

1. ORNL Computational Physics and Engineering Division.
2. Denison University, Granville, OH.
3. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
4. K. Wisshak et al., *Phys. Rev. C* **54**, 1451 (1996).
5. K. Wisshak et al., Forschungszentrum Karlsruhe report FZKA 5755 (1996).
6. H. Beer et al., *Astron. Astrophys.* **211**, 245 (1989).
7. R. Macklin and J. Gibbons, *Rev. Mod. Phys.* **37**, 166 (1965).

MEASUREMENTS OF ^{142,144}Nd(n,γ) CROSS SECTIONS AT ORELA FOR ASTROPHYSICAL *s*-PROCESS STUDIES

K. H. Guber,[1] R. R. Spencer,[2] P. E. Koehler, and R. R. Winters[3]

The identification of the *s*-process site in low-mass red giant stars on the asymptotic branch (AGB stars) has increased the interest in and need for improved neutron capture cross sections at lower temperature[4] because previous data do not cover this range. The major difference in these newer stellar *s*-process models is that the temperature of the site of nucleosynthesis is significantly lower, kT = 6 - 12 keV, than the canonical kT = 30 keV assumed in the classical *s*-process calculations.

The present interest in the (n,γ) cross sections of ^{142}Nd and ^{144}Nd is motivated by the following considerations: (i) ^{142}Nd is an *s*-only isotope; i.e., it is shielded against contribution from the *r*-process β-decay by its stable isobar ^{142}Ce and can only be produced by the *s*-process (neglecting the *p*-process). (ii) Recently discovered anomalies for the Neodymium isotopes are currently interpreted in terms of a pure *s*-process origin. With the previously extant data sets of ^{142,144}Nd (n,γ) cross sections, this interpretation could not be confirmed.

The measurements were performed at the 40-m flight station of the white neutron source ORELA. The experimental arrangement used for the neutron capture measurements is described elsewhere.[5] To fit the capture data obtained by our experiment we used the multilevel R-matrix code SAMMY.[6] From the resonance parameters together with the data from the unresolved region we obtained the astrophysical reactivity data. The (n,γ) cross section measurements at lower energies are very important, because the extrapolation of the data to lower temperatures could be wrong due to missing resonance parameters; previous measurements had a lower energy threshold at 3-5 keV. The Maxwellian cross section at 10 keV has a 20% contribution from resonances below 5 keV for ^{142}Nd and 25% for ^{144}Nd respectively. Our new measurements yield a Maxwellian cross section of 45.8±1.7 mb for ^{142}Nd at 30 keV and 83.9±2.5 mb for ^{144}Nd respectively. This is lower by 6% than the previous measurements[7] for ^{142}Nd and 30% for ^{144}Nd. At 10 keV the difference is even more dramatic, we measure 73.2±2.5 mb for ^{142}Nd, which is 30% lower, and 132.6±4.2 mb for ^{144}Nd, which is 50% lower.

From the new (n,γ) cross sections for ^{142}Nd and ^{144}Nd and the calculation performed with the most recent parameters, we draw the following conclusions: With the now approximately 30% lower cross section for ^{144}Nd at 30 keV we find an *s*-process pattern of the isotopic ratios ^{142}Nd/^{143}Nd/^{144}Nd/^{145}Nd/^{146}Nd/^{148}Nd for the classical model as follows: 1.84±0.13/0.36±0.02/1/0.17±0.036/0.92±0.053/0.04±0.003 compared to the value obtained from the Murchison meteorite[8] which is 2.13±0.08/0.29±0.006/1/0.161±0.005/ 0.775±0.009/0.0281±0.0058. Our network calculations at 12 keV with the new rates yield good agreement for the observed isotopic anomalies except for ^{142}Nd, whereas the classical model results differ from the observations for both ^{142}Nd and ^{144}Nd. This remaining difference for ^{142}Nd shows that there might still be a problem for the stellar model or that the meteorite abundances do not arise from pure *s*-process material. Due to the much lower ^{144}Nd cross section, the calculated *r*-process abundance is smaller and fits much better in a smooth *r*-process pattern obtained from the classical model.

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1. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
2. ORNL Computational Physics and Engineering Division.
3. Denison University, Granville, OH.
4. O. Straniero et al., *Astrophys. J.* **440**, L85 (1995).
5. P. E. Koehler et al., *Phys. Rev. C* **54**, 1463 (1996).
6. N. M. Larson, Technical Report No. ORNL/TM-9179/R2, Oak Ridge National Laboratory, 1989.
7. G. J. Mathews, F. Käppeler, *Astrophys. J.* **286**, 810 (1984).
8. S. Richter et al., *Nuclei in the Cosmos '92*, edited by F. Käppeler and K. Wisshak (Institute of Physics, Bristol, 1993), p. 127.

A BaF_2 DETECTOR SYSTEM FOR (n,γ) CROSS SECTION MEASUREMENTS AT ORELA

K. H. Guber,[1] P. E. Koehler, R. R. Spencer,[2] and R. R. Winters[3]

Recent progress in isotopic abundance measurements and in stellar models has demonstrated that further progress in understanding the *s*- and *p*-process nucleosynthesis requires new (n,γ) data. Measurements are needed at lower energies with greater precision, and on several isotopes having very small natural abundances. To decrease the time needed for these measurements and to decrease the size of the expensive isotopically enriched samples needed for the measurements, we have been developing a new γ-ray detector. A 4π-BaF_2 detector array was chosen because it is significantly more efficient than our current C_6D_6 detectors. One potential problem with this detector is its sensitivity to background caused by sample-scattered neutrons. However, the excellent TOF resolution obtainable at ORELA together with the good pulse-height resolution of BaF_2 makes it possible to overcome this background in most cases. By using the multiplicity information of the γ-ray cascade the S/N ratio can be improved further (see Fig. 2.24). The array consists of 12 hexagonal detectors which are 14 cm long by 8.7 cm wide.

In Fig. 2.25, small sections of the TOF data taken with a 1.65-g sample of ^{197}Au are shown. The solid curves represent the data after the sample-independent background corrections. The dotted curves show the background due to sample scattered neutrons. The data in Fig. 2.25 show that although the total efficiency of a BaF_2 detector of this size for capturing scattered neutrons is about 10%, the size of the prompt component of this background is much smaller. Hence, by virtue of the excellent TOF resolution at ORELA, the S/N ratio in the resolved resonance region is very good for most resonances. The background can be sizable for resonances having a large scattering-to-capture ratio, but the background is measurable, and in most cases so small that our detector is expected to yield good results.

Although these first measurements demonstrate that the detector works very well, there is room for improvement. We expect that this detector will be extremely useful for *s*- and *p*-process measurements, as well as helping determine *r*-process abundances more precisely.

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ORNL-DWG 96-7937

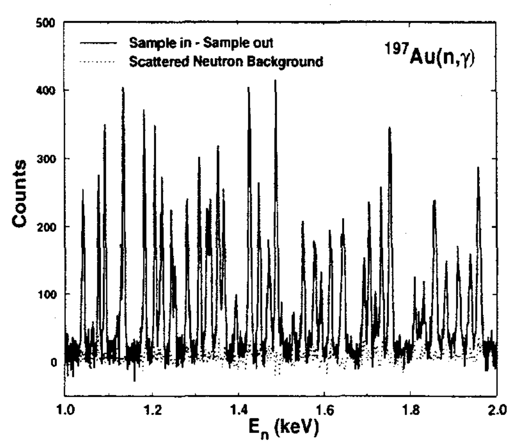

Fig. 2.24

ORNL-DWG 96-7938

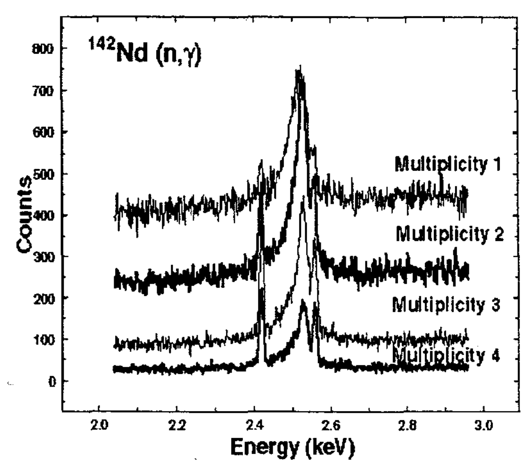

Fig. 2.25

NEW HIGH PRECISION TRANSMISSION MEASUREMENTS ON ^{208}Pb AT ORELA AND THEIR IMPACT ON THE ELECTRIC POLARIZABILITY OF THE NEUTRON

K. H. Guber,[1] P. Riehs,[2] S. Kopecky,[2] J. A. Harvey,[1] N. W. Hill,[1] R. F. Carlton,[3] and R. R. Winters[4]

As confirmed by electron-nuclear-scattering experiments at high energies, hadrons are not point-like objects. Because of the internal structure of the neutron; i.e., consisting of one up and two down quarks surrounded by a π^--meson cloud, the characteristics of their charge structure are the electric (α) and magnetic (β) polarizabilities. Since the net charge of the neutron is zero, it is a perfect candidate for determining the electrical polarizability of the nucleonic hadrons. So, in principal, the neutron should be polarizable in a strong electromagnetic field. The field strength obtained by macroscopic electric fields in laboratories is not strong enough to measure this effect. Therefore, the only way to obtain a value for the electric polarizability is to measure this effect in a strong electric field like that of a heavy nuclide.[5] Due to the interaction of this induced electric dipole moment of the neutron, an additional potential term must be added to the nuclear potential in calculating the nuclear interaction of the neutron. The total neutron-nucleus potential scattering cross section below 100 keV can then be parametrized[5] by

$$\sigma_s(k) = \sigma_s(0) + ak + bk^2 + O(k^4)$$

where k is the wave vector of the incoming neutron. The parameter a, which is linear in k, depends only on the electric polarizability of the neutron. The terms in higher orders of k describe the effective range of the neutron-nucleus interactions. To measure the polarizability, the total cross section of a very simple, heavy nucleus with few parameters has to be determined. The double magic ^{208}Pb is a perfect and very well suited candidate for this kind of experiment because it has relatively few parameters.

We have recently completed transmission measurements on thorogenic ^{208}Pb (72%) compensated with a radiogenic ^{206}Pb sample (88%) which leads to 100% ^{208}Pb. The measurements were performed at the Oak **R**idge **E**lectron **L**inear **A**ccelerator (**ORELA**) in the energy range from 2 eV to 2 MeV. High resolution transmission data were obtained at neutron flight path of 80 m and 200 m in the energy range from 10 keV up to 2 MeV in order to obtain more precise information on the neutron-nucleus potential and the resonance parameters. We used the multi-level *R*-matrix code SAMMY[6] for the resonance analysis and obtained an excellent fit to the experimental 80- and 200-meter data (see Fig. 2.26). With an additional measurement at a much shorter time-of-flight distance of 18 m from the neutron target, we covered the low energy range from 2 eV to 50 keV where the effect of the electric polarizability is the largest. From a careful fit to these data including all determined resonance parameters and $R_{external}$, we will obtain a new value for the electric polarizability of the neutron.

ORNL-DWG 96-7936

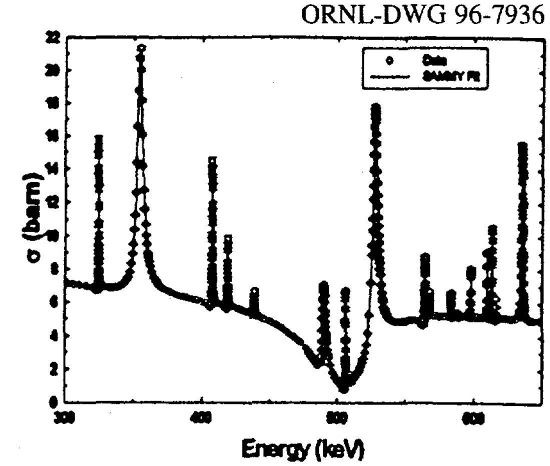

Fig. 2.26

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5. J. Schmiedmayer, P. Riehs, J. A. Harvey and N. W. Hill, *Phys. Rev Lett.* **66**, 1015 (1991).
6. N. M. Larson, Technical Report No. ORNL/TM-9179/R3, Oak Ridge National Laboratory, 1996.

EXPLOSIVE NUCLEOSYNTHESIS REACTION RATE NETWORK CALCULATIONS

M. S. Smith, A. Mezzacappa, and M. Gupta[1]

A computer code is being written to describe the synthesis of isotopes and the generation of energy occurring in explosive astrophysical environments such as novae, supernovae, and X-ray bursts. This code will be used to guide the choice of astrophysical capture reactions on radioactive isotopes that will be measured at the Holifield Radioactive Ion Beam Facility, as well as to fully investigate the astrophysical implications of such measurements. The code solves the system of coupled, non-linear, first-order differential equations which govern the time-evolution of the initial abundances of a set of isotopes to their final abundances. A crucial input for the code is a set of thermonuclear reaction rates, given as analytical functions of temperature. The inverses of these reactions are also included in the calculation, as these are important at the high temperatures (over 1 billion degrees) which may occur in X-ray bursts and in the shock wave of supernova explosions. The time-evolution of the abundances is determined with a fully implicit method of calculation that is unconditionally numerically stable. It involves inverting a matrix whose elements depend on the current abundances, the reaction rates (and therefore the stellar temperature), and the density. The code currently tracks the abundances of isotopes up to ^{21}Na, which interact via a small number (36) of reactions. However, the matrix is automatically generated, allowing additional isotopes and reactions to be easily added by modifying the appropriate input files. We are in the process of including all the reactions (160) and isotopes in the Caughlan and Fowler[2] compilation of nuclear reaction rates. Currently, the code can run at constant stellar temperatures and densities or with pre-defined time-varying temperature and density profiles. The code is, however, written so that the nucleosynthesis can be coupled (in the near future) to the hydrodynamics of the astrophysical systems. This coupling, which will allow a more accurate simulation of stellar explosions, will begin in the near future.

A shell for the code has been written to allow the investigation of the quantitative effect of nuclear physics (reaction rate) uncertainties on the nucleosynthesis predictions. Specifically, the shell allows the determination of the sensitivity of the final abundances to the input reaction rates – such as those we hope to measure at HRIBF – through systematic variations of the reaction rates. We have recently obtained the first preliminary results of such sensitivity analyses. The shell can also vary the reaction rates over their 1-sigma uncertainty via a Monte Carlo prescription, to quantitatively determine the resulting 1-sigma uncertainty of the abundance predictions. This allows, for example, the determination of the effect of making a new measurement – that is, reducing a reaction rate uncertainty – on the uncertainty of the predicted abundance of a particular isotope. It also allows the comparison of the abundance prediction uncertainties resulting from nuclear physics (e.g., reaction rates) to those resulting from astrophysics (e.g., stellar temperature and density). The sensitivity analyses and Monte Carlo analyses can also be combined to quantitatively determine if the rate resulting from a new measurement has a statistically significant effect on the abundance prediction. These techniques, some of which were previously utilized in big bang nucleosynthesis studies,[3] have not been used in studies of explosive nucleosynthesis. Our future work will be to expand the reaction network and then to couple the network to hydrodynamics.

A number of visualization techniques are also being explored to facilitate the interpretation of these calculations. One technique involves the generation of a diagram of the total flow of one isotope into another (after the calculation is completed), displayed on a chart of the nuclides (proton number vs. neutron number). Animating a series of such diagrams gives insight into changes in isotopic flow with time. Another involves making sequences of charts of the nuclides, where predicted abundances are indicated by color intensity at any time, and then animating the sequence to show the time evolution of the abundances.

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2. G. R. Caughlan, W. A. Fowler, *At. Data Nucl. Data Tables* **40**, 283 (1988).
3. M. S. Smith et al., *Astrophys. J. Suppl.* **85**, 219 (1993).

NUCLEAR DATA EVALUATION FOR NUCLEAR ASTROPHYSICS

M. S. Smith, B. H. Cain,[1] *M. Gupta,*[2] *D. C. Larson, and D. W. Bardayan*[3]

Nuclear astrophysics involves study of the synthesis of elements and the evolution of cosmic sites where these syntheses occur. Systems as diverse as the early universe, the interstellar medium, red giant stars, and supernova explosions are currently the intense focus of many research programs both within and outside the U.S. Computer models of such exciting astrophysical phenomena require a very diverse set of nuclear physics information to ascertain the rates of and energy released in nuclear reactions occurring in astrophysical environments. The rates are derived from laboratory measurements of cross sections of relevant reactions, and much information on the properties (e.g., masses, lifetimes, level densities) of the nuclei involved in astrophysical processes are also required. Astrophysical models have a *crucial dependence* on the completeness, precision, and timeliness of this input nuclear data. New measurements of crucial reaction rates, for example, can significantly alter our models of astrophysical phenomena.

There currently is no mechanism through which nuclear physics measurements are routinely collected, evaluated, put into a form compatible with astrophysical models, and distributed to the community. For example, one of the most widely used compilations of reaction rates[4] has not been updated since 1988, and therefore does not contain any of the measurements made over the last eight years. This poor utilization of nuclear physics measurements has resulted in studies of astrophysical systems which are based on outdated nuclear data. Progress in many fundamental problems in nuclear astrophysics would be significantly aided by establishing a coordinated U.S. data effort to provide sets of evaluated data for nuclear astrophysics studies. Recently, a Steering Committee has been formed (with ORNL membership) and a Task Force (with an ORNL chair) to set data priorities, to obtain the involvement of the nuclear astrophysics research community, to document the overlap of the nuclear data and nuclear astrophysics community,[5] and to coordinate the efforts of U.S. researchers to produce a set of standard files available to all astrophysics modelers. An organized effort within the U.S. will also facilitate coordination with international nuclear data efforts. These organizational efforts have resulted in the possibility of the U.S. D.O.E. to fund a nuclear astrophysics data center, and ORNL has submitted a proposal to host this center.

In addition, the nuclear astrophysics data needs of the on site experimental and theoretical nuclear astrophysics research programs are being met through a number of small projects. For example, we need to incorporate the analytical expressions for 160 thermonuclear reaction rates (and their inverses) in the Caughlan and Fowler[4] compilation into a new ORNL nucleosynthesis reaction rate network code. Since this extremely valuable, published compilation of reaction rates has never been disseminated electronically, we have entered these rates into a computer in the form of a downloadable FORTRAN subroutine which will be posted on the ORNL Physics Division WWW site. We are also calculating the temperature derivatives of these rates, useful for coupling nucleosynthesis calculations to hydrodynamics. On-line tabular data for these rates, and plots, are also planned. Another project (described in a separate progress report) involves determining the current best rates for the $^{14}O(\alpha,p)^{17}O$ and $^{17}F(p,\gamma)^{18}Ne$ reactions based on indirect measurements, in order to prepare for measurements of these reactions with radioactive ion beams at HRIBF.

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3. Yale University, New Haven, CT.
4. G. R. Caughlan, W. A. Fowler, *At. Data Nucl. Data Tables* **40**, 283 (1988).
5. M. S. Smith, F. E. Cecil, R. B. Firestone, G. M. Hale, D. C. Larson, D. A. Resler, "U.S. Nuclear Data Resources for a Coordinated U.S. Effort in Nuclear Data for Nuclear Astrophysics," Report from the Astrophysics Task Force of the U.S. Nuclear Reaction Data Network, unpublished (http://www.dne.bnl.gov/~burrows/usnrdn/astrodata.html).

EXPRESSIONS FOR THE $^{14}O(\alpha,p)^{17}F$ AND $^{17}F(p,\gamma)^{18}Ne$ ASTROPHYSICAL REACTION RATES

D. W. Bardayan,[1] M. S. Smith, and A. García[2]

There are a number of extremely hot, dense astrophysical environments where hydrogen is expected to burn explosively. These include supermassive stars, X-ray bursters, novae, and supernovae. The hot-CNO cycle, $^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(e^{+}n_e)^{14}N(p,\gamma)^{15}O(e^{+}n_e)^{15}N(p,\alpha)^{12}C$, is the reaction sequence through which such burning occurs at temperatures less than $\approx 2 \times 10^8$ K. At high temperatues it can be bypassed by the faster $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}N(e^{+}n_e)^{18}F(p,\alpha)^{15}O$ reaction sequence, which increases the energy generation rate and alters the abundances of the CNO nuclides. An accurate prediction of both the thermonuclear energy generation and the detailed isotopic composition of nuclei synthesized is the goal of the modeling of these complex astrophysical events. These models require expressions for the relevant reaction rates as analytic functions of the stellar temperature. We have generated analytic expressions for the $^{14}O(\alpha,p)^{17}F$ and $^{17}F(p,\gamma))^{18}Ne$ stellar reaction rates using the *most recent* indirect experimental measurements of relevant reaction parameters.

The $^{14}O(\alpha,p)$ reaction rate was calculated using resonance parameters measured by Hahn et al.[3] and the direct capture parameters from Funck *et al.*[4] Interference between the two components was accounted for, and the rate agreed with that reported in Ref. 3. The calculation was then fit over the temperature range most important for novae, $0.1 < T_9 < 1.0$ (where $T_9 = T/10^9$ K), with a nine-parameter expression similar in form to one reported in Caughlan and Fowler.[5] Work is ongoing to extend the temperature range of the fit to $0.001 < T_9 < 10.000$ to cover (almost) all scenarios important in nuclear astrophysics.

The $^{17}F(p,\gamma))$ reaction rate was calculated using resonance and direct capture parameters from García *et al.*[6] There is no significant interference between the resonances and the direct capture partial waves. The calculated reaction rate differs from that originally reported in Ref. 6 due to an error in calculating the contribution from the 4.52 MeV resonance. Because of this error, the rate in ref. 6 was 13% too low at T_9 = 1. The reaction rate was then fit over the temperature range $0.02 < T_9 < 1.00$ with an expression similar to ones in ref. 5; the result is shown in Fig. 2.27. We are working to extend the temperature range of this fit to $0.001 < T_9 < 10.000$.

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1. Yale University, New Haven, CT.
2. University of Notre Dame, Notre Dame, IN.
3. K. I. Hahn et al., *Phys. Rev. C* **54**, 1999 (1996).
4. C. Funck et al., *Nucl. Phys.* **A480**, 188 (1988).
5. G. R. Caughlan and W. A. Fowler, *At. Data Nucl. Data Tables* **40**, 283 (1988).
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ORNL-DWG 96-7940

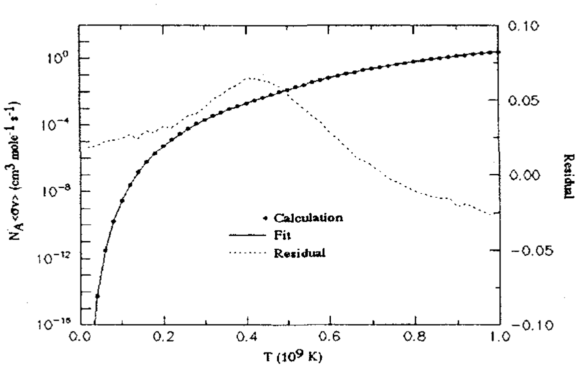

Fig. 2.27. The $^{17}F(p,\gamma)$ reaction rate fit and residuals.

ABSTRACTS OF PAPERS PUBLISHED OR SUBMITTED FOR PUBLICATION

NUCLEAR STRUCTURE

IDENTICAL BANDS IN DEFORMED AND SUPERDEFORMED NUCLEI[1]

C. Baktash, B. Haas,[2] and W. Nazarewicz[3]

The observation of rotational bands in different nuclei that have unexpectedly identical moments of inertia and, sometimes, identical γ-ray energies has excited the low-energy nuclear physics community recently. These identical bands exist at both low and high spins, and they span a wide variety of shapes that range from weakly oblate, to normal, moderately large, and super-prolate deformations. The pervasive occurrences of identical bands point to the rigidity of the even-even nuclei with respect to the polarization forces of the unpaired valence nucleons. This unexpected stability has posed a serious challenge to theoretical models.

1. Abstract of published paper: *Annu. Rev. Nucl. Part. Sci.* **45**, 485-541 (1995).
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3. University of Tennessee, Knoxville.

ARE OCTUPOLE VIBRATIONS HARMONIC?[1]

M. P. Metlay,[2] J. L. Johnson,[2] J. D. Canterbury,[2] P. D. Cottle,[2]
C. W. Nestor, Jr.,[3] S. Raman, and V. G. Zelevinsky[4]

The anharmonicity of octupole vibrations is deduced over a wide range of Z and A through the examination of summed $B(E3)\uparrow$ values for all 3^- states in a given nuclide versus the centroid energy for those states. Data obtained with the (p,p'), (d,d'), and (α,α') reactions are used, as opposed to an earlier study based on Coulomb excitation and lifetime data. Results of the new analysis support earlier observations of significant anharmonicity, but leave open the possibility of greater harmonicity than was previously supposed. Fits to the experimental data are discussed within the framework of the hydrodynamical model and possible mechanisms for the observed behavior are suggested.

1. Abstract of published paper: *Phys. Rev. C* **52**, 1801 (1995).
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3. University of Tennessee, Knoxville.
4. Michigan State University, East Lansing.

NEUTRON-PROTON CORRELATIONS IN SELF-CONJUGATE NUCLEI[1]

J. D. Garrett

Values of the double binding energy difference for even-even nuclei,

$$\Delta_{np} = -\{[B(N, Z) - B(N-2, Z)] - [B(N, Z-2) - B(N-2, Z-2)]\}/4,$$

are compared in Fig. 2.28 with the neutron–neutron and proton–proton pair gaps (Δ_{nn} and Δ_{pp}) for self-conjugate nuclei with A = 8 – 72. (Δ_{nn} and Δ_{pp} are calculated using the four-mass formulae from, *e.g.*, Ref.1.) The near equality of Δ_{np}, Δ_{nn}, and Δ_{pp} for self-conjugate nuclei over this sizable range of nuclear masses (all the existing data) provides a nice confirmation of the interpretation of Δ_{np} as the interaction strength associated with the "last" neutron and the "last" proton as well as the charge independence of the nuclear force. It also negates the fallacy that for self-conjugate nuclei T = 0 pair correlations are larger than T = 1 pair correlations. The decrease of these quantities as a function of mass can be understood in terms of the nuclear size and the spatial localization of the valence nucleons.

Data also is available for the isospin dependence of Δ_{np}, Δ_{nn}, and Δ_{pp}, indicating that Δ_{np} decreases more rapidly with increasing T_Z (neutron excess) than either Δ_{nn} or Δ_{pp}. In addition, Δ_{nn} decreases with increasing T_Z somewhat faster than Δ_{pp}.

Theoretical interpretation of these findings is underway in collaboration with the ORNL/UT nuclear structure group.

ORNL-DWG 97-5499

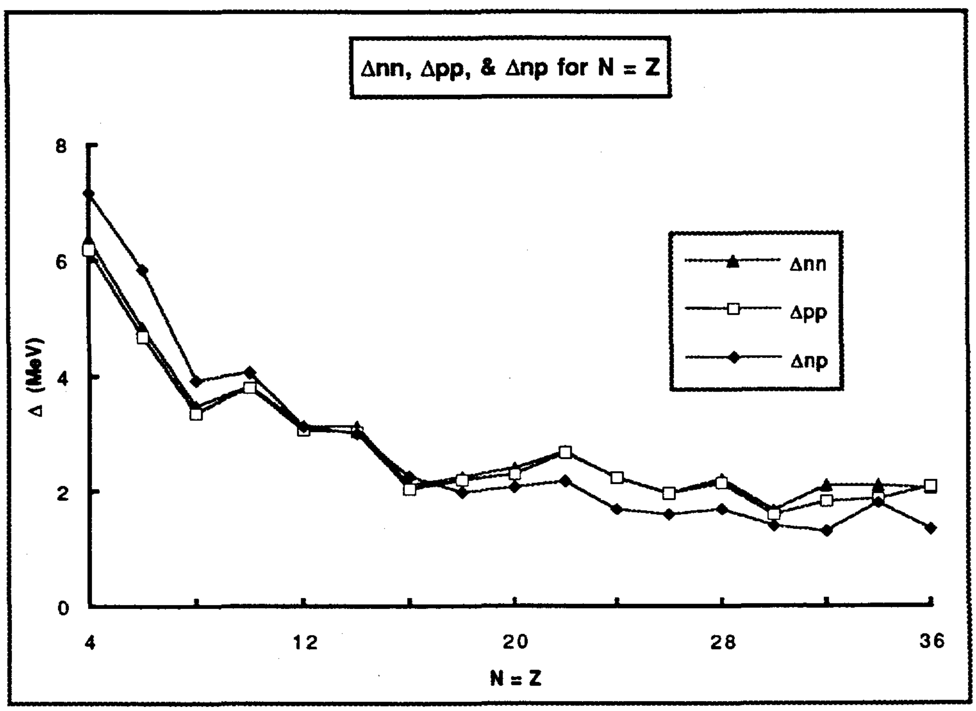

Fig. 2.28. Variation of Δnp, Δnn, and Δpp as a function of N (and Z) for self-conjugate (N=Z) nuclei.

1. Abstract of paper published in *Proceedings of the Conference on Nuclear Structure at the Limits*, Argonne National Laboratory, July 22-27, 1996.

NUCLEAR LEVEL REPULSION AND "ORDER" VS. "CHAOS"[1]

J. D. Garrett, J. Q. Robinson,[2] A. J. Foglia,[3] and H.-Q. Jin[4]

This contribution describes a statistical analysis of the distribution of level spacings for states with the same I^{π} in which the average spacing is calculated for the total ensemble of states of given I^{π} in even-even, odd-even, or even-odd nuclei. Though the resulting distribution of 3130 level spacings for states of deformed nuclei with Z = 62 – 75 and A = 155 – 185 is the closest to that of a Poisson distribution yet obtained for nuclear levels, significant deviations are observed for small level spacings (Fig. 2.29). Such deviations, observed independent of spin, parity, nuclear type (even-even, even-odd, or odd-even), and intrinsic nuclear excitation (Fig. 2.30), are attributed to the level repulsion associated with the mixing of closely spaced states with identical I^{π}. These data indicate that this mixing becomes increasingly important in deformed rare-earth nuclei for separations < 60 keV; however, a few spacings for as small as 1 keV do remain. Such data imply interactions, V_{int}, varying between a few and about 30 keV.

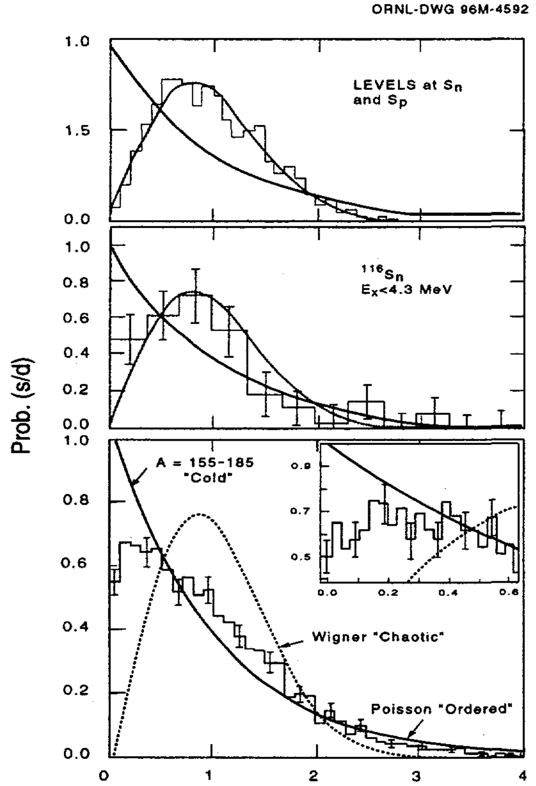

Fig. 2.29. Comparison of level-spacing distributions (histograms) for nuclear states with the same Iπ for "cold deformed rare-earth nuclei" with curves corresponding to Poisson and Wigner distributions associated with "ordered" and "chaotic" behavior, respectively. The insert shows the rare-earth data for the close spacings with a smaller bin size.

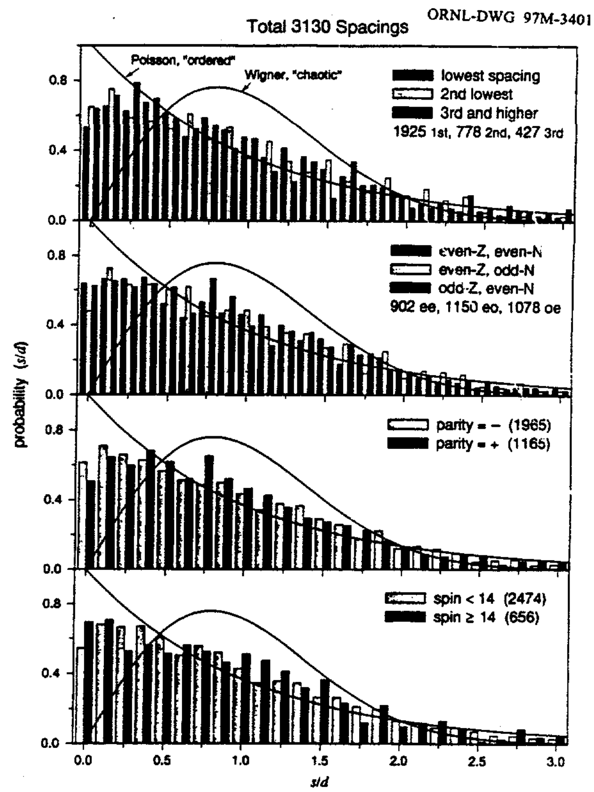

Fig. 2.30. Level-spacing distributions as a function of excitation energy (i.e., lowest, second-lowest, ...), nuclear type, parity, and angular momentum.

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DISTRIBUTION OF VERY-CLOSELY-SPACED LEVELS WITH THE SAME I^{π} IN RARE EARTH NUCLEI [1]

H.-Q. Jin[2] *and J. D. Garrett*

To demonstrate the physical basis of the very small interaction matrix elements associated with closely-spaced levels of the same spin and parity, the distribution of the 76 level spacings in the deformed rare-earth nuclei ($Z = 62 - 75$ and $A = 155 - 185$) with $\leq$10 keV are summarized in Fig. 2.31. Closely-spaced levels are observed for both parities, for even-even and for odd-A nuclei, and at low and high spin corresponding roughly with their occurrence in the data ensemble. Whereas the distribution as a function of spacing is skewed toward the larger spacings, values of <1 keV are observed, for example, between $I^{\pi} = 11/2^-$ states in ^{159}Er. The observed asymmetry between positive- and negative-parity states with spacings $\leq$10 keV in odd-A nuclei is the result of different densities of positive- and negative-parity single-particle (Nilsson) states near the Fermi level. For example, in the $N = 82 - 126$ neutron shell, which is being filled for the nuclei considered, there are 30 negative-parity neutron states (corresponding to the Nilsson components of the $h_{9/2}$, $f_{7/2}$, $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$, shell-model states) and 14 positive-parity states (corresponding to the components of the $i_{13/2}$, intruder states) spanning nearly the same excitation energy range. Hence an excess of closely-spaced negative-parity levels are expected for odd-N nuclei, as is observed. For protons, which fill the next lower shell (with 20 $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$, positive-parity states and 12 $h_{11/2}$, negative-parity states) the opposite is true.

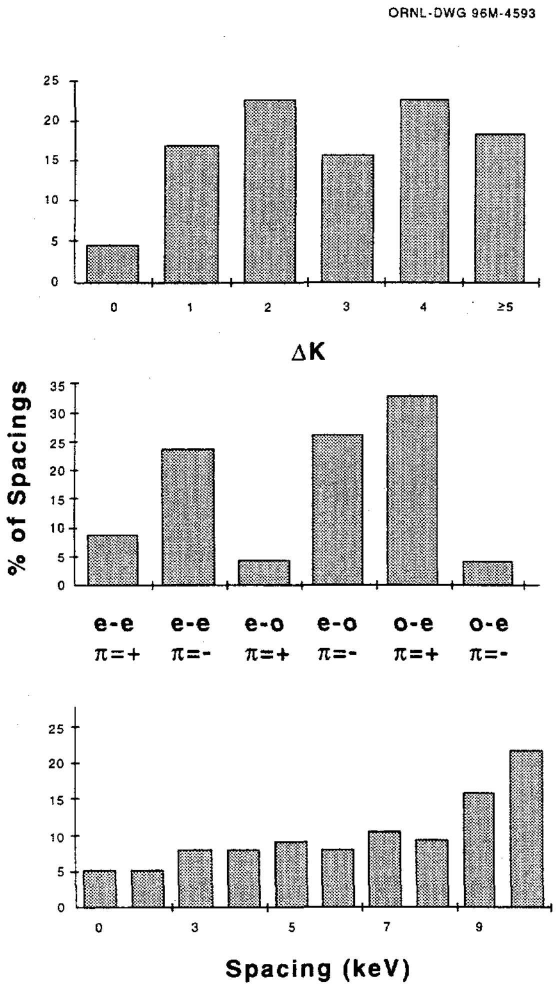

Fig. 2.31. Distribution of the 76 closely-spaced ($\leq$10 keV) levels in the rare-earth region with identical values of I^{π} as a function of K-value difference, ΔK, (top); nuclear type and parity, π, (middle); and level spacing, ΔE (bottom). o-e refers to odd-Z even-N, etc.

Probably the most striking feature of the closely-spaced levels is the correlation with the K quantum number. Fifty-seven percent of the closely-spaced levels with known K-values correspond to states that differ in K by three or more units, and 80 percent are associated with states differing in K by two or more units. Hence the majority, but perhaps even more interestingly, not all of the close spacing can be attributed to the conservation of the K quantum number in these deformed nuclei.

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1. Abstract of published paper: *Proceedings of the Conference on Nuclear Structure at the Limits*, Argonne National Laboratory, July 22-27, 1996.
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NUCLEAR LEVEL REPULSION, ORDER VS. CHAOS AND CONSERVED QUANTUM NUMBERS[1]

J. D. Garrett, J. R. German,[2] and J. M. Espino[3]

A statistical analysis of the distribution of level spacings for states with the same angular momentum and parity is described in which the average spacing is calculated for the total ensamble. Though the resulting distribution of level spacings for states of deformed nuclei with Z = 62-75 and A = 155-185 is the closest to that of a Poisson distribution yet obtained for nuclear levels, significant deviations are observed for small level spacings. Many, but not all, of the very closely spaced levels have K-values differing by several units.

1. Abstract of published paper: *Response of the Nuclear System to External Forces*, ed. J. M. Aries et al. (Springer, 1995, Berlin), p. 263.
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3. Departamento de Fisica Atomica, Molecular y Nuclear, Universidad de Sevilla, Sevilla, Spain.

SPECTROSCOPY OF ^{20}F LEVELS[1]

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From a study of the ^{19}F(n,γ) reaction with thermal neutrons incident on a Teflon target, 168 γ rays have been detected and incorporated into a level scheme of ^{20}F consisting of 35 previously known levels and a new one at 5939 keV. Two low-energy primary $E1$ transitions of energies 584 and 665 keV together account for more than half of the total capture cross section. They populate, respectively, states at 6018 and 5936 keV (both J^{π}=2$^-$). These states are also excited strongly in the ^{19}F(d,p) reaction. From each of these states, 17 γ rays were observed to the lower-lying states. These γ rays constitute the largest number of branches reported from any nuclear bound state. A weak (6 ± 1μb) γ ray of energy 4630.6 ± 0.9 keV, placed as a transition between the neutron-capturing state (which is a 0$^+$ and 1$^+$ mixture) and the 1971-keV, (3$^-$) state, might represent the first observation of a primary $M2$ transition in the (n,γ) reaction. The total thermal-neutron-capture cross section of ^{19}F was measured as 9.51 ± 0.09 mb; and the neutron separation energy of ^{20}F as 6601.35 ± 0.04 keV. Estimates of direct neutron capture have been made using physically realistic optical-model parameters. These model estimates are in reasonable agreement with the measured (partial) cross sections. While constructing the (n,γ) level scheme, the existing data on bound levels in ^{20}F were critically evaluated. The lifetime values for many levels are poorly known. Therefore, the lifetimes for 25 levels were measured by the Doppler-shift-attenuation method using the inverse reaction ^{2}H(^{19}F, $p\gamma$) on implanted deuterium targets. The experimental level properties such as excitation energies, J^{π} assignments, branching ratios, and lifetimes have been compared with the results from a large-basis shell-model calculation. The agreement was found to be quite good, but this comparison points out also the need for acquiring new data to give more definitive J^{π} assignments.

1. Abstract of published paper: *Phys. Rev. C* **53**, 616 (1996).
2. Deceased, Brookhaven National Laboratory, Upton, NY.
3. Los Alamos National Laboratory, Los Alamos, NM.
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STRUCTURE OF ODD-ODD ^{72}As: EXPERIMENT AND THEORY[1]

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The levels in ^{72}As have been studied employing the ^{59}Co(^{16}O, 2pn) reaction with the Bucharest tandem and the ^{47}Ti(^{28}Si, 3p) reaction at 95 MeV with the HHRIF tandem to enhance high spin states. New high-spin states have been observed beginning at 1179.5 keV, and they include a cascade up to 6092.2 keV tentatively assigned (17$^+$). These results are compared with the theoretical calculations based on the VAMPIR models which also include neutron-proton mixing.

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1. Abstract of published paper: *J. Phys. G: Nucl. Part. Phys.* **22**, 1013-1024 (1996).
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6. Universität Tübingen, Tübingen, Germany.
7. University of Tennessee, Knoxville.
8. Idaho Nuclear Engineering Laboratory, Idaho Falls, ID.
9. Louisiana State University, Baton Rouge.
10. Wayne State University, Detroit, MI.
11. Lawrence Berkeley National Laboratory, Berkeley, CA.

ROTATIONAL BANDS IN ^{76}Rb (Ref. 1)

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High spin states in ^{76}Rb were investigated via the reaction ^{40}Ca(^{40}Ca,^{3}*pn*)^{76}Rb at 128 MeV. The level scheme was established from $\gamma\gamma$, $\gamma\gamma\gamma$ and recoil-γ coincidences measured in the EUROGAM I array in combination with the Daresbury recoil separator. The known rotational bands were extended up to the excitation energy $E_x \approx 9.2$ MeV and spins $I^{\pi} = (21^+)$ and (19^-). The band head energies could be fixed by many interband transitions. Two new bands were identified. The level scheme is discussed in terms of the cranked shell model. In the negative parity bands ^{76}Rb behaves like a rigid rotor until the first band crossings.

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1. Abstract of published paper: *Phys. Rev. C* **51**, 6 (1995).
2. Physikalisches Institut, Germany.
3. Oak Ridge Institute for Science and Education /ORNL, Oak Ridge, TN.
4. Daresbury Laboratory, Daresbury, United Kingdom.
5. Chalmers University of Technology, Gothenberg, Sweden.
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7. University of Manchester, Manchester, United Kingdom.

A NEW TYPE OF BAND CROSSING AT LARGE DEFORMATION[1]

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A detailed study of the positive parity yrast and yrare rotational bands in ^{77}Rb is presented. Using the reaction ^{40}Ca(^{40}Ca,3*p*) and the EUROGAM I spectrometer, $\gamma\gamma\gamma$ coincidences enabled us to follow both bands over a large spin range and to measure many E2 strengths. The moments of inertia and transition quadrupole moments indicate that a more deformed band ($\varepsilon_2 \approx 0.38$) is crossed by a less deformed one ($\varepsilon_2 \approx 0.29$). Since the yrare band starts at the extremely low spin value of $I = 9/2$, the conventional band crossing mechanism of two aligning high-j quasiparticles is excluded. The frequency-dependent equilibrium shapes were calculated with Nilsson-Strutinsky type calculations using a diabatic tracing of configurations near the neutron Fermi level. This is the first observation of such a band crossing.

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1. Abstract of published paper: *Phys. Lett.* **B374**, 277-282 (1996).
2. Universität Göttingen, Göttingen, Germany.
3. Institut für Kern-Hadronenphysik, Dresden, Germany.
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7. Chalmers University of Technology, Göteborg, Sweden.
8. University of Manchester, Manchester, United Kingdom.

FIRST OBSERVATION OF A SUPERDEFORMED BAND IN THE $N,Z \approx 40$ MASS REGION[1]

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A high-spin rotational band of ten transitions between 1305 and 2641 keV with a nearly constant moment of inertia $\Im^{(2)} = 27\hbar^2$ MeV^{-1} has been observed and is tentatively assigned to ^{83}Sr. The properties of this band are in excellent agreement with theoretical calculations which predict the onset of superdeformation in and around ^{83}Sr at spins $I \approx 35\hbar$. These results establish a new region of superdeformation in medium-mass nuclei with particle numbers N,Z $\approx$ 40.

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1. Abstract of published paper: *Phys. Rev. Lett.* **74**, 1946 (1995).
2. University of Liverpool, Liverpool, United Kingdom.
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4. Joint Intitute for Heavy Ion Research, Oak Ridge, TN.
5. University of Tennessee, Knoxville.
6. Washington University, St. Louis, MO.
7. Daresbury Laboratory, Warrington, United Kingdom.
8. Warsaw University, Warsaw, Poland.

CHARACTERIZATION OF THE FIRST SUPERDEFORMED BAND IN THE $A \approx 80$ REGION[1]

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The recently discovered superdeformed band in one of the strontium isotopes has been identified as belonging to ^{83}Sr from a study with the Gammasphere array and the Microball charged-particle detector system. From its decay pattern, a spin of (81 ± 2)/2 $\hbar$ is deduced for the highest level of this band. Evidence for very fast transition rates and agreement of the characteristics of this band with the theoretical predictions establish the yrast superdeformed nature of this band in ^{83}Sr.

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1. Abstract of published paper: *Phys Lett.* **B354**, 34-40 (1995).
2. Washington University, St. Louis, MO.
3. Lawrence Berkeley National Laboratory, Berkeley, CA.
4. University of Pittsburgh, Pittsburgh, PA.
5. Florida State University, Tallahassee.
6. Oak Ridge Institute for Science and Education /ORNL, Oak Ridge, TN.
7. Rutgers University, New Brunswick, NJ.
8. Michigan State University, East Lansing.
9. University of Tennessee, Knoxville.
10. Warsaw University, Warsaw, Poland.

RESULTS FROM GAMMASPHERE IN THE $A \approx 80$ MASS REGION[1]

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We present recent results obtained with GAMMASPHERE for nuclei in the $A \approx 80$ mass region. These studies have concentrated on a systematic study of superdeformed bands and their transitional quadrupole moments. Normally-deformed rotational bands in a series of even-even $T_z = 1$ nuclei were also investigated to probe the possible influence of the *np* pairing on the structure of their yrast bands.

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1. Abstract of paper submitted to *Zeitschrift für Physik A.*
2. Oak Ridge Institute for Science and Education /ORNL, Oak Ridge, TN.
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6. Lawrence Berkeley National Laboratory, Berkeley, CA.

MULTIPLE SUPERDEFORMED BANDS IN ^{81}Sr (Ref. 1)

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Four superdeformed bands extending over five to twelve transitions have been identified in ^{81}Sr from a study with the Gammasphere array and the Microball charged-particle array. One of the bands shows an upbend in the dynamic moment of inertia at a rotational frequency of 1.2 MeV and all bands exhibit a nearly constant moment of inertia below that frequency.

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1. Abstract of published paper: *Phys. Lett.* **B357**, 281-286 (1995).
2. University of Pittsburgh, Pittsburgh, PA.
3. Washington University, St. Louis, MO.
4. Lawrence Berkeley National Laboratory, Berkeley, CA.
5. Florida State University, Tallahassee.
6. Oak Ridge Institute for Science and Education /ORNL, Oak Ridge, TN.
7. Michigan State University, East Lansing.
8. University of Tennessee, Knoxville.
9. Warsaw University, Warsaw, Poland.

SYSTEMATICS OF EVEN-EVEN $T_Z = 1$ NUCLEI IN THE $A = 80$ REGION: HIGH-SPIN ROTATIONAL BANDS IN ^{74}Kr, ^{78}Sr, ^{82}Zr, AND ^{86}Mo (Ref. 1)

D. Rudolph, C. Baktash, I. Birriel,[2] M. Devlin,[3] C. J. Gross,[4] H.-Q. Jin, D. R. LaFosse,[3] F. Lerma,[3] J. X. Saladin,[2] D. G. Sarantites,[3] W. Satula,[5] G. Sylvan,[6] S. L. Tabor,[6] D. Winchell,[2] V. Wood,[2] and C.H. Yu

High-spin states of $T_Z = 1$ nuclei were studied by means of the reactions ^{58}Ni(^{28}Si,3α)^{74}Kr, ^{58}Ni(^{28}Si,2α)^{78}Sr, and ^{58}Ni(^{28}Si,2p2n)^{82}Zr at 130 MeV beam energy. The GAMMASPHERE array in conjunction with the 4π charged-particle detector array MICROBALL was used to detect γ rays in coincidence with evaporated light charged particles. The known $\pi = +$, $\alpha = 0$ yrast bands were extended to I = 28 ħ at 20 MeV excitation energy. For all three nuclei, a number of positive- and negative-parity side-bands were established: altogether 15 new rotational bands. The data are discussed using the pairing-and-deformation self-consistent total routhian surface (TRS) model.

ORNL-DWG 97-5424

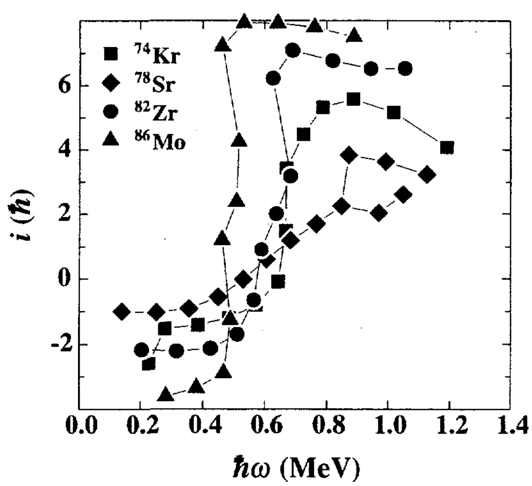

Fig. 2.32. Shows the alignment of the $\pi = +$ yrast bands of the four $T_Z = 1$ nuclei. The bands are observed to very high rotational frequencies beyond the first proton and neutron $g_{9/2}$ band crossings. The simultaneous alignment of protons and neutrons in ^{74}Kr is confirmed. The alignment gain ~ 8ħ is similar to that in ^{82}Zr.

ORNL-DWG 97-5425

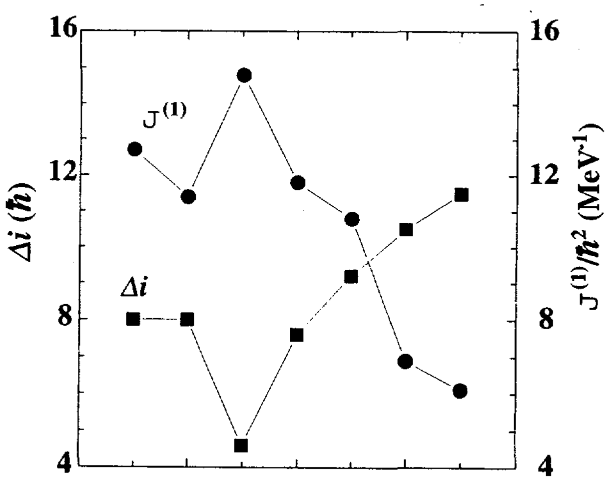

Fig. 2.33. Alignment gain at ħω = 1.0 MeV.

1. Abstract of paper submitted to *Physical Review C.*
2. University of Pittsburgh, Pittsburgh, PA.
3. Washington University, St. Louis, MO.
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FORKING AND UNUSUAL DECAY OUT OF SUPERDEFORMED BANDS IN ^{83}Zr (Ref. 1)

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Two superdeformed (SD) bands extending over nine to eleven transitions have been identified in ^{83}Zr. The quadrupole moment of the more intense band was determined by the Residual Doppler Shift Method and is consistent with a quadrupole deformation of $\beta_2 \approx 0.5$. The large quadrupole moment and population intensity of the yrast SD band ($\approx$ 5%) in Zr isotopes relative to their isotones in Sr and Y nuclei suggest the presence of a large SD shell gap at proton number Z = 40. At the decay-out points, the Routhians of the SD bands reapproach that of the positive parity normally deformed states which may be the reason why both of these bands feed mainly ($\approx$ 85%) into the positive-parity yrast band.

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1. Abstract of paper submitted to *Physics Letters B*.
2. University of Pittsburgh, Pittsburgh, PA.
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IDENTIFICATION AND QUADRUPOLE-MOMENT MEASUREMENT OF A SUPERDEFORMED BAND IN ^{84}Zr (Ref. 1)

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High-spin states in ^{84}Zr were studied using the early implementation phase of the Gammasphere array and the "Microball" charged-particle detector system. A cascade of nine γ rays with a dynamic moment of inertia which is characteristic of superdeformed rotational bands in the A = 80 region has been identified and assigned to ^{84}Zr. The measured transition quadrupole moment of the band corresponds to a prolate quadrupole deformation of $\beta_2 = 0.53$ and confirms the superdeformed nature of this band. This is the first direct experimental confirmation of the existence of the predicted superdeformed shell gap at N = 44 particle number.

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1. Abstract of published paper: *Phys. Rev. Lett.* **75**, 8 (1995).
2. Oak Ridge Institute for Science and Education/ORNL, Oak Ridge, TN.
3. Washington University, St. Louis, MO.
4. Lawrence Berkeley National Laboratory, Berkeley, CA.
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SHELL-MODEL INFLUENCE IN THE ROTATIONAL NUCLEUS ^{86}Mo (Ref. 1)

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High-spin states in ^{86}Mo were studied by means of the fusion evaporation reaction ^{58}Ni(^{32}S,2p2n) ^{86}Mo at 135 MeV beam energy. Charged-particle-$\gamma\gamma$ and -$\gamma\gamma\gamma$ coincidences recorded with the early implementation of the GAMMASPHERE array and the MICROBALL charged-particle detection system were used to largely extend the level scheme of the $T_Z = 1$ nucleus ^{86}Mo to a possible spin of $I = 24\hbar$ at 13 MeV excitation energy. The excitation scheme is compared to neighboring nuclei. There is evidence for enhanced shell-model influence in the 4 quasiparticle region ($I = 12$-$16\hbar$). The observed ($\pi = +$, $\alpha = 0$) sequence at spin $I \geq 16\hbar$ appears to be associated with a triaxial collective rotational band. This interpretation is supported by calculations within the configuration-dependent shell-correction approach with the cranked Nilsson potential.

1. Abstract of published paper : *Phys. Rev. C* **54**, 1 (1996).
2. Oak Ridge Institute for Science and Education/ORNL, Oak Ridge, TN.
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5. Washington University, St. Louis, MO.
6. Lawrence Berkeley National Laboratory, Berkeley, CA.
7. Lund Institute of Technology, Lund, Sweden.

STRUCTURE OF ^{108,110,112}Ru: IDENTICAL BANDS IN ^{108,110}Ru (Ref. 1)

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The levels in ^{108,110,112}Ru have been investigated in the spontaneous fission of ^{252}Cf by using γ-γ-γ, γ-γ-, x-x-, x-γ and x-γ-γ-coincidence techniques. The levels up to 16^+ and 9^+ in the yrast bands and γ-vibrational bands, respectively, have been identified with very little energy staggering in ^{108,110,112}Ru. The ground bands in ^{108,110}Ru have identical γ-ray transition energies up to 8^+. These are the lightest observed even-even nuclei with extended identical ground bands. Calculations in a collective model, which includes rotations and vibrations, reproduce the level energies and γ-band branching ratios above the 3^+ state rather well, while rigid triaxial rotor model calculations reproduce the branching ratios for the 2^+ and 3^+ states.

1. Abstract of published paper: *Phys. Rev. C* **52**, 52 (1995).
2. Vanderbilt University, Nashville, TN.
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DEFORMATION OF LIGHT XENON ISOTOPES[1]

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Recently measured $B(E2;0_1^+ \rightarrow 2_1^+)$ values for the light xenon (Z = 54) isotopes show a marked increase in deformation as the neutron numbers approach the midshell value of N = 66. At first sight, this behavior is anomalous because the 2_1^+ level energies are nearly the same for these isotopes. Moreover, this increase is not readily explained by several nuclear models that assign single shells to valence protons and neutrons. In particular, the single-shell asymptotic Nilsson model with current parameters seriously underpredicts the $B(E2;0_1^+ \rightarrow 2_1^+)$ values for $^{118}Xe_{64}$, $^{120}Xe_{66}$, and $^{122}Xe_{68}$. On the other hand, several modern multishell models correctly predict these values. We examine the latter results more closely to find ways in which the single-shell asymptotic Nilsson model can be revised to correctly reproduce the measurements. We also show that the $B(E2;0_1^+ \rightarrow 2_1^+)$ values for lighter (N < 66) barium isotopes, when they are measured, will test the predictive power of existing systematics and modeling of quadrupole deformations in nuclei.

1. Abstract of published paper: *Phys. Rev.* C **52**, 1380 (1995).
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EVIDENCE FOR CONTINUUM *E*0 TRANSITIONS FOLLOWING THE DECAY OF HIGH SPIN STATES IN ^{130}Ce (Ref. 1)

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The decay of high-spin states in the continuum of ^{130}Ce is studied via γ-ray and internal conversion electron spectroscopy. An electron surplus above predicted yields based on γ-ray data is seen in coincidence with transitions in the yrast band of ^{130}Ce. We attribute this to an admixture of electric monopole (*E*0) transitions with unstretched *E*2 and Ml transitions between strongly interacting bands of different deformations in the continuum. The *E*0 matrix elements needed to explain this surplus are comparable in magnitude to reponed *E*0 matrix elements between discrete states in neighboring nuclei.

1. Abstract of published paper: *Phys. Rev. C* **53**, 652 (1996).
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3. Present address: Lawrence Berkeley National Laboratory, Berkeley, CA.
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OCTUPOLE DEFORMATION IN ^{142,143}Ba AND ^{144}Ce: NEW BAND STRUCTURES IN NEUTRON-RICH Ba-ISOTOPES[1]

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New high-spin band strutures are established for the neutron-rich nuclei ^{142,143,145,147}Ba, and ^{144}Ce, and levels of ^{144,146}Ba are extended to higher spins from the study of γ-γ and γ-γ-γ coincidence experiments in spontaneous fission. Alternating parity sequences connected by strong electric dipole transitions are identified in ^{142,143}Ba and ^{144}Ce but not in ^{145,147}Ba to confirm theoretical predictions of stable octupole deformation for $N = 86$.

1. Abstract of published paper: *Phys. Lett.* **B357**, 273-280 (1995).
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EVIDENCE FOR HYPERDEFORMATION IN ^{147}Gd (Ref. 1)

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A pair of rotational bands with 9 and 11 discrete γ rays with a regular spacing of about 29 keV extending from 1016 to 1340 keV have been identified as belonging to ^{147}Gd. Evidence from their population, decay characteristics, very large dynamic moments of inertia of $\Im^{(2)} = 140\hbar^2$ MeV^{-1}, and agreement with theoretical predictions support the hyperdeformed character of these bands. These band structures correspond to a spheroid with major-to-minor axis ratio of about 3:1.

1. Abstract of published paper: *Phys. Rev. Lett.* **74**, 26 (1995).

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6. Warsaw University, Warsaw, Poland.

SEARCH FOR HYPERDEFORMATION IN ^{146,147}Gd (Ref. 1)

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A search was undertaken to look for evidence of hyperdeformation in ^{146,147}Gd. Three experiments employing Gammasphere for gamma-ray detection coupled with the Microball for channel selection via charged-particle detection were carried out with increasing detection sensitivity and statistics. No definitive evidence for band structures that could be assigned to hyperdeformation could be found. Candidates previously reported are shown not to have properties consistent with hyperdeformed bands.

1. Abstract of published paper: *Phys. Rev. C* **54**, 1585 (1996).
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SEARCH FOR LINKING TRANSITIONS IN ^{143}Eu (Ref. 1)

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A search has been performed in order to confirm/extend the summed γ-energy linking transitions reported for the superdeformed (SD) band in ^{143}Eu.[1] The reaction ^{100}Mo(^{51}V,α4n) with E_{beam} = 230 MeV was employed to populate the known SD band in ^{143}Eu. The Gammasphere array, consisting of 57 detectors, and the Microball, a 4π array of CsI light charged particle detectors were used to collect the approximately 10^9 α-gated events. The Microball, in addition to cleanly selecting the α-xn events, was used to correct the momentum direction of the recoiling nuclei due to α-emission. This yielded a significantly improved γ-ray energy resolution due to more precise Doppler correction.

ORNL-DWG 97-5423

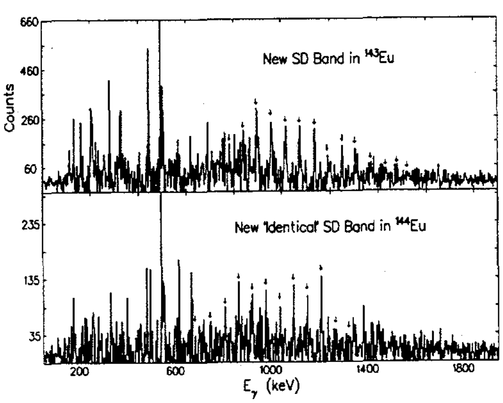

Fig. 2.34. New identical bands in ^{143}Eu and ^{144}Eu isotopes.

1. Abstract of paper submitted to *Physical Review C.*
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IDENTIFICATION OF ^{152}Ce AND UNEXPECTED VARIATIONS IN MOMENTS OF INERTIA WITH NEUTRON NUMBER AND SPIN IN $^{142\text{-}148}$Ba, $^{144\text{-}152}$Ce AND $^{146\text{-}156}$Nd (Ref. 1)

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Levels in ^{152}Ce are identified for the first time along with the new high-spin states in $^{142\text{-}148}$Ba, $^{144\text{-}150}$Ce and $^{150\text{-}156}$Nd from x-x, γ-x and γ-γ-γ coincidence measurement in spontaneous fission of ^{252}Cf and ^{242}Pu. The $N = 88$, 90 Ba nuclei have very nearly identical J_1 for the yrast bands (2^+ to 10^+) and for the octupole bands (3^- to 15^-). The $N = 92$, 94 Nd nuclei have essentially identical yrast J_1 (0^+ to 16^+).

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1. Abstract of published paper: *J. Phys. G: Nucl. Part. Phys.* **21**, L75-L81 (1995).
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IDENTIFICATION OF LEVELS IN ^{160}Sm AND NEW HIGH-SPIN STATES IN ^{156,158}Sm (Ref. 1)

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From γ-γ, x-x, x-γ, and γ-γ-γ coincidence studies of spontaneous fission of ^{252}Cf, ^{160}Sm levels were identified along with new high-spin states in ^{156,158}Sm. New bands, beginning at 5^- in ^{156,158}Sm, are assigned a two-neutron configuration $\{5/2^+[642], 5/2^-[523]\}5^-$. The J_1 and J_2 values for the yrast bands increase smoothly with spin and neutron number, and the differences in these values for corresponding transitions in neighboring isotopes are reasonably constant.

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1. Abstract of published paper: *J. Phys. G: Nucl. Part. Phys.* **21**, L57-L62 (1995).
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SEARCH FOR TWO-PHONON GAMMA VIBRATIONAL STATES IN ^{164}Dy (Ref. 1)

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Excited states in ^{164}Dy were produced using Coulomb excitation. Rotational properties of the gound-state and gamma-vibrational band were studied. Angular distribution and band-mixing parameters were extracted from the data. No evidence was found for a two-phonon gamma vibration with anharmonicity in the range $1.7 \leq E(4^+_{\gamma\gamma}) / E(4^+_{\gamma}) \leq 2.7$.

1. Abstract of published paper: *Phys. Rev. C* **51**, 2952 (1995).
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EVOLUTION OF COLLECTIVITY TO VERY HIGH SPINS IN ^{160}Yb (Ref. 1)

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Lifetimes of ^{160}Yb yrast states at high rotational frequencies have been measured by the Doppler-broadened line shape technique. Excited states in ^{160}Yb were populated by the reaction ^{120}Sn(^{44}Ca,4*n*)^{160}Yb at a beam energy of 200 MeV and the experimental measurements were carried out in the coincidence mode with an array of Compton-suppressed germanium detectors. The results for the 24^+ to 32^+ yrast states led to values of the transition quadrupole moments similar to those obtained for the lower members ($\hbar\omega \leq 0.29$ MeV) of the ground band in previous recoil-distance measurements. The trend of reducing Q_t values found for the $I = 34^+$ and 36^+ states are suggestive of band termination. The results are discussed in the light of current theoretical predictions.

1. Abstract of published paper: *Phys. Rev. C* **53**, 671 (1996).
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THE LOSS OF COLLECTIVITY AT HIGH SPINS IN ^{164}Yb AND ITS NEIGHBORING EVEN-EVEN NUCLEI[1]

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Lifetimes of high-spin states in ^{164}Yb have been measured by the Doppler-broadened line shape (DBLS) method using the reaction ^{124}Sn(^{44}Ca, 4n) ^{164}Yb at a bombarding energy of 189 MeV. The Q_t values from the data decrease sharply over the rotational frequency range 0.3 to 0.5 MeV (I = 20 to 32 $\hbar$). At the same rotational frequencies the kinematic moment of inertia is nearly constant, increasing slightly at the higher frequencies) $\hbar\omega$ = 0.40 to 0.55 MeV. These observations can be understood qualitatively as a rotationally induced deoccupation of strongly shape polarizing anti-aligned high-j, low- Ω orbitals, i.e., those in which the nucleons are moving in the opposite direction to the rotation. A summary of the Q_t values extracted from the lifetime data for the yrast decay sequences of the even-A nuclei $^{160\text{-}168}$Yb are compared with the deformations from self-consistent cranking TRS calculations. The TRS calculations show the expected neutron number dependence, i.e., $\Delta\beta_2/\beta_2(\hbar\omega = 0.40)$ is smaller with increasing N and the corresponding loss of collectivity, Q_t vs $\hbar\omega$, has a smaller slope at the larger $\hbar\omega$ with increasing N. For ^{164,166,168}Yb the loss of collectivity from the DBLS measurements occurs at higher $\hbar\omega$ than predicted and the slope of Q_t vs $\hbar\omega$ is much larger than predicted. The enhanced El/E2 branching ratios and the large transition dipole moments for decay of the states in the (-, 1) band to the ground band and the (+, 0) band in ^{164}Yb suggest an octupole instability for ^{164}Yb.

1. Abstract of published paper: *Nucl. Phys.* **A599**, 560 (1996).
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HIGH-SPIN STATES IN ODD-ODD ^{164}Lu (Ref. 1)

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High-spin states in odd-odd ^{164}Lu have been studied using ^{19}F- and ^{23}Na-induced fusion-evaporation reactions. Three strongly coupled rotational bands have been established and three decoupled bands were tentatively assigned to ^{164}Lu. The band crossing frequencies, energy signature splittings, and relative transition probabilities were deduced from experimental data and compared with neighboring even-even and odd-A nuclei. An anomalously large band crossing frequency was observed in the excited band, and a pronounced signature inversion was observed in the yrast band of ^{164}Lu. These anomalies may be associated with residual neutron-proton interactions.

1. Abstract of paper submitted to *Nucl. Phys.* **A608**, 74 (1996).
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HIGH-*K* THREE-QUASIPARTICLE ROTATIONAL BANDS IN ^{171}Hf (Ref. 1)

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High-spin states have been populated in ^{171}Hf with the ^{48}Ca + ^{128}Te reaction at 200 MeV. A three-quasiparticle strongly coupled rotational band has been established in ^{171}Hf which is built upon the known $K^\pi = 19/2^+$, 6.2 ns, isomeric state. In addition, the strongly coupled band built upon the $K^\pi = 23/2^-$, 18 ns, isomeric state in ^{171}Hf has been extended to higher excitation energy. $(g_K - g_R)/Q_0$ values, determined from the $\Delta I = 2$ to $\Delta I = 1$ branching ratios, have been used in combination with the aligned angular momentum to confirm the configuration assignments for each band. Three new γ-ray transitions have also been established in ^{171}Hf which link the $K^\pi = 19/2^+$, 6.2 ns, isomeric bandhead state directly into the yrast states. The reduced hindrance factors for these decays are discussed.

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HIGH-SPIN STATES AND *K*-FORBIDDEN DECAY IN ^{172}Hf (Ref. 1)

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High-spin states were populated in ^{172}Hf with the ^{48}Ca + ^{128}Te reaction at 200 and 214 MeV. All of the known rotational bands in ^{172}Hf have been extended and five new rotational bands have been observed using the Gammasphere spectrometer. This study establishes the highest known state in ^{172}Hf at spin $44\hbar$. One of the new bands is a $K^\pi = (14^+)$ strongly coupled rotational band. In conflict with the K-selection rule another newly established bandhead state, with spin I = K = 12, is observed to γ decay directly to the yrast 12^+ state. This large breakdown in the K-selection rule ($\Delta K \approx 12$) may be due to a mixing between the low- and high-K states in ^{172}Hf.

1. Abstract of published paper: *Phys. Rev. C* **52**, 5 (1995).
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QUADRUPOLE COLLECTIVITY AND SHAPES OF Os-Pt NUCLEI[1]

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E2 collective properties for the low-lying states in ^{186,188,190,192}Os and ^{194}Pt have been investigated experimentally by means of Coulomb excitation using 3.3-4.8 MeV/nucleon ^{40}Ca, ^{58}Ni, ^{136}Xe and ^{208}Pb beams. The deexcitation γ rays following Coulomb excitation were detected in coincidence with the scattered particles. Levels with excitation energies up to 3-4 MeV of the ground-state, γ and 4^+ collective bands as well as excited 0^+ states were populated in each nucleus studied. A semiclassical Coulomb-excitation least-squares search code GOSIA was used to extract E2 matrix elements from the measured γ-ray yields. For each nucleus studied, a unique and almost complete set of E2 matrix elements for the low-lying states has been determined, which includes both the magnitudes and signs of the transitional and diagonal matrix elements. The completeness of the set of measured E2 matrix elements makes it possible to determine the intrinsic quadrupole deformation for the low-lying states in these nuclei via a model-independent method. The results indicate clearly that the E2 properties for the low-lying states in these nuclei are correlated well using only the quadrupole collective degrees of freedom. The extracted E2 matrix elements are compared with the prediction of various collective models such as the asymmetric rigid rotor model, the γ-soft model of Leander, and the IBA-2 model. These particular models do not reproduce the data satisfactorily; however, the general trends of the data are consistent with the descriptions of γ-soft type collective models through a prolate to oblate shape-transition region. That the enhanced B(E2) values between the I,quasi-K^π = $4,4^+$ state and members of the I,quasi-K^π = $2,2^+$ band are well reproduced by the γ-soft model is consistent with the interpretation of the I,quasi-K^π = $4,4^+$ state being a two-phonon γ-vibration excitation.

1. Abstract of published paper : *Nucl. Phys.* **A607**, 178-234 (1996).
2. University of Rochester, Rochester, NY.
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PROLATE-OBLATE BAND MIXING AND NEW BANDS IN ^{182}Hg (Ref. 1)

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In-beam γ-ray spectroscopic studies of ^{182}Hg have revealed five new bands. The 2^+ state of the prolate band has been identified at an energy of 548.6 keV and is higher than in ^{184}Hg. A two-parameter band mixing calculation results in an interaction energy of 83 keV between the prolate 2^+ and the oblate 2^+ states. Several additional new bands are seen, including some which are interpreted as quadrupole vibrational bands built on the excited prolate minimum.

1. Abstract of published paper: *Phys. Rev. C* **51**, 401 (1995).
2. Vanderbilt University, Nashville, TN.
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NEW HIGH-SPIN BAND STRUCTURES IN ^{184}Hg (Ref. 1)

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The high-spin states in ^{184}Hg have been investigated via the ^{154}Gd (^{32}S,4*n*) reaction at a beam energy of 160 MeV, with an array of Compton-suppressed Ge detectors in the Spin Spectrometer at HHIRF. The ground state oblate band and excited prolate band were extended to 10^+ and 26^+, respectively, and seven new bands are observed. A new band with off-spins, 13 to 25, has a much larger moment of inertia than the other bands in ^{184}Hg. Two of the new bands feed the prolate excited band and are interpreted as quadrupole vibrational bands. Also, two new signature partner bands are observed for which the configuration of $\nu i_{13/2} f_{7/2}$ is proposed. The similarity of the band with odd spins to the band with intermediate deformation ($\beta_2 \sim 0.34$) n ^{186}Hg, and signature partner bands to the bands observed in 104 isotones ^{180}Os and ^{182}Pt, is discussed.

1. Abstract of published paper: *Phys. Rev. C* **52**, 595 (1995).
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GAMMA-RAY TRANSITIONS IN ^{206}Pb STUDIED IN THE ^{205}Pb(n,γ) REACTION[1]

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A study of the γ-ray spectrum following thermal-neutron capture by ^{205}Pb has revealed 54 γ rays, which have been incorporated into a level scheme consisting of 22 excited states in ^{206}Pb. This study was carried out with an ~9 mg-lead sample enriched to 78.9% in radioactive ^{205}Pb. The neutron binding energy of ^{206}Pb was determined to be 8086.67 ± 0.06 keV, and the thermal-neutron-capture cross section for ^{206}Pb to be 4.5 ± 0.2 b. The low-lying portion of the level scheme of ^{206}Pb and the γ-ray branchings of positive-parity states have been compared with shell-model predictions. The overall agreement is excellent for the former and reasonably good for the latter.

1. Abstract of published paper: *Phys. Rev. C* **53**, 2732 (1996).
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PROTON RADIOACTIVITY STUDIES AT THE FMA[1]

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The decays of ^{146,147}Tm, ^{160}Re, and ^{156}Ta were reinvestigated at the ATLAS linear accelerator facility of Argonne National Laboratory using the Argonne fragment mass analyzer and a double-sided silicon strip detector. Testing the setup, confirming the previous results, and improving the precision of measurements were goals of these experiments. The decay energies and half-lives were found to be in good agreement with previous results. Improved statistics were obtained for ^{160}Re and ^{156}Ta proton decays. A β-decay branching of the order of 50% was observed in the decay of the ^{156}Ta ground state which is in contrast to but agrees well with the expected β-decay half-life of the ^{156}Ta ground state. The quality of the collected data was sufficient to encourage further searches of new ground state proton emitters in heavier masses.

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1. Abstract of published paper: *ENAM 95, International Conference on Exotic Nuclei and Atomic Masses* (Editions Frontieres, Gif-sur-Yvette, France, 1995), pp. 313-314.
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DISCOVERY OF THE HEAVIEST KNOWN PROTON EMITTERS ^{167}Ir AND ^{171}Au USING THE ARGONNE FRAGMENT MASS ANALYZER[1]

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A sequence of odd-Z proton radioactivities has previously been established from Z = 69-75. In the present experiment performed at Argonne National Laboratory, a ^{78}Kr beam was used to bombard a ^{96}Ru target at energies of 370 and 420 MeV. Fusion-evaporation reaction products were separated from the beam using the Fragment Mass Analyzer and were implanted into a double-sided silicon strip detector where subsequent decays were measured. At the lower beam energy, alpha decays from the new isotope ^{171}Au produced via the 1p2n evaporation channel were clearly visible. Following a time- and position-correlation analysis, a proton decay branch from ^{171}Au was clearly identified as preceding the known alpha decay of ^{170}Pt. At the higher beam energy proton radioactivity was also identified from the nucleus ^{167}Ir which was produced via the α1p2n channel. In this case the proton decay was correlated with the known α-decay of ^{166}Os. The discovery of proton emission in ^{167}Ir and ^{171}Au gives a continuous sequence of 6 odd-Z proton emitting elements. Furthermore, this represents the heaviest points, Z = 77 and 79, at which the proton drip line has been crossed to date. The results will be discussed in the paper.

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1. Abstract of published paper: *ENAM 95, International Conference on Exotic Nuclei and Atomic Masses* (Editions Frontieres, Gif-sur-Yvette, France, 1995), pp. 263-268.
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PROSPECTS FOR STUDIES OF GROUND-STATE PROTON DECAYS WITH THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

K. S. Toth

By using radioactive ions from the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory, it should be possible to identify many new ground-state proton emitters in the mass region from Sn to Pb. During this production and search process the limits of stability on the proton-rich side of the nuclidic chart will be delineated for a significant fraction of medium-weight elements and our understanding of the proton-emission process will be expanded and improved.

1. Abstract of published paper: *Revista Mexicana de Fisica* **40**, Suplemento 1, 170 (1994).

DECAYS OF $^{160-162}$Hf (Ref. 1)

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The α and β decays of $^{160-162}$Hf were measured following their productions in ^{135}Ba(^{32}S,*xn*) reactions. For the first time γ transitions following ^{160}Hf β decay were observed. Partial β-decay schemes of ^{161,162}Hf are presented and the α decay rates of ^{160}Hf and ^{162}Hf are discussed within the systematics of $0^+ \rightarrow 0^+$ α reduced widths.

1. Abstract of published paper: *Phys. Rev. C* **52**, 2236 (1995).
2. University of Göttingen, Göttingen, Germany.
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IDENTIFICATION OF ^{166}Pt AND ^{167}Pt (Ref. 1)

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In a series of ^{78}Kr bombardments of ^{92}Mo the new isotopes ^{166}Pt and ^{167}Pt were identified *via* their α-decay properties. The α-decay energies and half-lives of these two nuclides are as follows: (1) ^{166}Pt, E_α = 7110(15) keV, $T_{1/2}$ = 0.3(1) ms, and (2) ^{167}Pt, E_α = 6988(10) keV, $T_{1/2}$ = 0.7(2) ms. Also, the half-life of ^{168}Pt, which was previously unknown, was determined to be 2.0(4) ms. In a separate but concurrent experiment involving ^{78}Kr + ^{96}Ru reactions, ^{170}Pt was made and a half-life of 14.7(5) ms was measured for it; the one published value is 6^{+5}_{-2} ms. Results for $^{162-164}$Os contained in the same data sets were also analyzed and by using mother-daughter correlations, the α branches of ^{162,163,164}Os were established to be near 100%.

1. Abstract of published paper: *Phys. Rev. C* **54**, R20 (1996).
2. Adjunct staff member from the University of Tennessee, Knoxville.
3. Louisiana State University, Baton Rouge.
4. Argonne National Laboratory, Argonne, IL.
5. Vanderbilt University, Nashville, TN.
6. Oregon State University, Corvallis.
7. University of Maryland, College Park.
8. Edinburgh University, Edinburgh, United Kingdom.

IDENTIFICATION OF ^{180}Pb (Ref. 1)

K. S. Toth, J. C. Batchelder,[2] D. M. Moltz,[3] and J. D. Robertson[4]

The α decay of the new isotope ^{180}Pb was observed in ^{40}Ca bombardments of ^{144}Sm: E_α = 7.23(4) MeV, and, $T_{1/2} = (4^{+4}_{-2})$ ms. With this decay energy and the known mass of ^{176}Hg, the mass excess of ^{180}Pb was calculated to be -1.98(5) MeV.

1. Abstract of published paper: *Z. Phys.* **A355**, 225 1996).
2. Louisiana State University, Baton Rouge.
3. Lawrence Berkeley National Laboratory, Berkeley, CA.
4. University of Kentucky, Lexington.

THE α-DECAY PROPERTIES OF ^{181}Pb (Ref. 1)

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The α-decay energy of ^{181}Pb has been measured as 7211 (10) and 7044 (15) keV. In the first study the isotope was produced in ^{90}Zr bombardments of ^{94}Mo and, after traversing a velocity filter, implanted in a position-sensitive Si detector; no half-life for ^{181}Pb was reported. In the second study the isotope was produced in ^{40}Ca bombardments of ^{144}Sm and transported to a position in front of a Si(Au) surface barrier detector with a fast He-gas-jet capillary system; an estimate of 50 ms was determined for the ^{181}Pb half-life. Recently we investigated ^{181}Pb α-decay at the Argonne National Laboratory ATLAS accelerator facility as part of a survey experiment in which a 1-pnA beam of 400-MeV ^{92}Mo was used to irradiate targets of ^{89}Y, ^{90,92,94}Zr, and ^{92}Mo to examine yields for one-and two-nucleon evaporation products from symmetric cold-fusion reactions. Recoiling nuclei of interest were passed through the Fragment Mass Analyzer and implanted in a double-sided silicon strip detector for α-particle assay. With the ^{90}Zr target we observed an α group at 7065 (20) keV which was correlated with A = 181 recoils and had a half-life of 45 (20) ms. There was no indication in these ^{90}Zr + ^{92}Mo data of the 7211 (10)-keV α particles seen by Keller et al. The interested reader is referred to the 1993 atomic mass evaluation wherein the input α-decay energies and resultant masses of the light Pb isotopes (including ^{181}Pb) are discussed.

1. Abstract of published paper: *ENAM 95, International Conference on Exotic Nuclei and Atomic Masses* (Editions Frontieres, Gif-sur-Yvette, France, 1995), pp. 607-608.
2. Louisiana State University, Baton Rouge.
3. University of Maryland, College Park.
4. University of Tennessee, Knoxville.
5. Argonne National Laboratory, Argonne, IL.

α-DECAY PROPERTIES OF ^{181}Pb (Ref. 1)

K. S. Toth, J. C. Batchelder,[2] C. R. Bingham,[3] L. F. Conticchio,[4] W. B. Walters,[4] C. N. Davids,[5] D. J. Henderson,[5] R. Herman,[5] H. Penttilä,[5] J. D. Richards,[6] A. H. Wuosmaa,[5] and B. E. Zimmerman[3]

The isotope ^{181}Pb was produced in ^{92}Mo bombardments of ^{90}Zr and, together with other reaction products, was passed through a recoil mass separator and implanted in a double-sided silicon strip detector for α-particle assay. The half-life and energy of the main ^{181}Pb α transition were determined to be 45 (20)

ms and 7065 (20) keV, respectively. This ^{181}Pb E_α agrees with one previously measured value [7044 (15) kev], but not with the one [7211 (10) keV] used as input to the 1993 Atomic Mass Evaluation. The 6180-keV α transition assigned to ^{181}Tl by Bolshakov et al. was observed, but the 6566-keV α particles ascribed to a 2.7-ms level in ^{181}Tl by Schneider were not.

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1. Abstract of published paper: *Phys. Rev. C* **53**, 2513 (1996).
2. Louisiana State University, Baton Rouge.
3. Adjunct staff member from the University of Tennessee, Knoxville.
4. University of Maryland, College Park.
5. Argonne National Laboratory, Argonne, IL.
6. University of Tennessee, Knoxville.

PROTON DECAY OF AN INTRUDER STATE IN ^{185}Bi (Ref. 1)

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The new proton radioactivity ^{185m}Bi has been observed, produced *via* the ^{95}Mo(^{92}Mo,*pn*)^{185}Bi reaction. Its decay proceeds from the low-lying $1/2^+$ intruder state in ^{185}Bi to the ^{184}Pb ground state with the emission of a proton of energy 1.585 ± 0.009 MeV and a half-life of 44 ± 16 μs. This marks the first observation of proton radioactivity above the Z = 82 closed shell, and it has been used to obtain the admixture of a 0^+ intruder state in ^{184}Pb into the ^{184}Pb ground-state wave function.

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1. Abstract of published paper: *Phys. Rev. Lett.* **76**, 592 (1996).
2. Argonne National Laboratory, Argonne, IL.
3. University of Edinburgh, Edinburgh, United Kingdom.
4. University of Maryland, College Park.
5. University of Jyväskylä, Jyväskylä, Finland.
6. Louisiana State University, Baton Rouge.
7. University of Tennessee, Knoxville.
8. Vanderbilt University, Nashville, TN.
9. Oregon State University, Corvallis.

EXCITATION ENERGY OF THE $\pi s_{1/2}$ INTRUDER STATE IN ^{189}Bi (Ref. 1)

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In a series of ^{48}Ti bombardments of ^{144}Sm the decay energy of the ^{189}Bi^m ($\pi s_{1/2}$) α transition that proceeds to the ($\pi s_{1/2}$) ground state of ^{185}Tl was measured to be 7.30(4) MeV. This result establishes the excitation energy of ^{189}Bi^m as 190(40) keV rather than the adopted 92(10)-keV value. Our data indicate a leveling off in excitation energy at N ≈ 106 for the $s_{1/2}$ intruder state in the odd-A Bi isotopes rather than a continued drop at that neutron number as inferred by Coenen et al. in their discussion of intruder state systematics in the Pb region. Consequences of this discrepancy for the adopted excitation energy of the $\pi s_{1/2}$ isomer in ^{187}Bi are discussed.

1. Abstract of published paper: *Phys. Rev. C* **52**, 1807 (1995).
2. Louisiana State University, Baton Rouge.
3. Lawrence Berkeley National Laboratory, Berkeley, CA.
4. University of Tennessee, Knoxville.

STUDY OF ^{189m}Bi α DECAY[1]

J. C. Batchelder,[2] K. S. Toth, D. M. Moltz,[3] T. J. Ognibene,[3] M. W. Rowe,[3] C. R. Bingham, E. F. Zganjar,[2] and B. E. Zimmerman[4]

The low-spin isomer in ^{189}Bi has been previously reported as having an α-decay energy of 7.206 ± 0.020 MeV and 7.34 ± 0.03 MeV. In a recent experiment we observed the α line from ^{189}Bi^{m} at an energy of 7.30 ± 0.05 MeV. This isotope was produced in the ^{144}Sm(^{48}Ti,p2n) reaction utilizing beams of 215, 220, and 230 MeV from the Lawrence Berkeley National Laboratory 88-Inch Cyclotron. Its α decay was observed by using the Rapidly Rotating Recoil Catcher Wheel system of the RAMA group at Lawrence Berkeley Laboratory. Catcher foils on the edge of the wheel are used to stop the recoils which are then rotated between two arrays of Si detectors in series. Using the difference in the number of counts in consecutive detectors, a preliminary half-life of 7.0 ± 0.2 ms was determined based on the observation of ~70 events. Previous measurements report half-lives of ~ 5 ms and 4 ± 2 ms. The α transition under discussion proceeds from the first excited (1/2$^+$) level in ^{189}Bi to the (1/2$^+$) ground state of ^{185}Tl. Its energy, combined with that of the (9/2$^+$) ^{189}Bi ground state (which also decays to the ^{185}Tl ground state) establishes the excitation energy of the (1/2$^+$) isomer in ^{189}Bi as 220 ± 50 keV. Plots of level energies versus N for intruder states in Tl, Pb, and Bi nuclei all show parabola-shaped curves with minima at N ≈ 110 except for the (1/2$^+$) states in odd-A Bi isotopes. This curve, based on the 7.206 MeV α-decay energy of ^{189}Bi^{m} (and a resultant 92 keV excitation energy for the (1/2$^+$) isomer), shows a continued drop for N < 108. Our Q_α value suggests that this is not the case and that, as for intruder levels of neighboring Z, the excitation energies of (1/2$^+$) states have a minimum at N ≈ 110.

1. Abstract of published paper: *ENAM 95, International Conference on Exotic Nuclei and Atomic Masses* (Editions Frontieres, Gif-sur-Yvette, France 1995), pp. 541-542.
2. Louisiana State University, Baton Rouge.
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4. University of Tennessee, Knoxville.

OBSERVATION OF FINE STRUCTURE IN ^{190}Pb α DECAY[1]

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The α decay of mass separated ^{190}Pb was studied at the UNISOR on-line facility and fine structure was observed for the first time, feeding the 2^+_1 and 0^+_2 states in ^{186}Hg identified previously in β-decay and in-beam γ-ray studies. The hindrance factor of the α decay to the excited 0^+_2 state in ^{186}Hg is similar to that observed in ^{182,184}Hg. The variation of the hindrance factor to the 2^+_1 states in ^{182,184,186}Hg is discussed.

1. Abstract of published paper: *Phys. Rev. C* **54**, 2041 (1996).
2. University of Tennessee, Knoxville.
3. Lawrence Livermore National Laboratory, Livermore, CA.
4. Louisiana State University, Baton Rouge.
5. UNIRIB, Oak Ridge Institute for Science and Education, Oak Ridge, TN.

DETERMINATION OF THE ^{190}Po α REDUCED WIDTH[1]

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The isotope ^{190}Po was produced in the ^{144}Sm(^{48}Ti,*2n*) reaction and its α-decay energy and half-life were measured to be 7.49(4) MeV and $2.0^{+0.5}_{-1.0}$ ms, respectively. These data compare as follows with preliminary values reported by Quint et al.: E_{α} = 7482(20) keV and a $T_{1/2}$= $9.6^{+4.7}_{-4.4}$ ms. While the two energies agree, the half-lives differ by a factor of almost 5. The earlier data yield an α reduced width which is much smaller than those of neighboring nuclides; our ^{190}Po energy and half-life result in a width that fits the overall α-decay-rate systematics in the mass region above the Z = 82 closed shell.

1. Abstract of published paper: *Phys. Rev. C* **54**, 949 (1996).
2. Louisiana State University, Baton Rouge.
3. Lawrence Berkeley National Laboratory, Berkeley, CA.

DECAY CHAINS OF ^{202}Fr AND ^{204}Fr AND α DECAY BRANCHES[1]

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The decay chains of ^{202}Fr and ^{204}Fr were observed at the ISOLDE facility with Si(Au) α and Ge γ detectors. The activities were made by the bombardment of a ThC target with a pulsed 1-GeV proton beam, ionized with a positive surface ionization source, and directed from the General Purpose Separator along the low-mass beam line. The separations were rapid, resulting in a pulsed Fr beam at the collection station, in response to the pulsed proton beam; for the shorter activities, decay between beam pulses was followed by means of detectors at the collection spot. The collected samples periodically were moved via a tape to a counting station where decays of the longer-lived daughters were observed. The production rates were sufficiently high to get quite good statistics for the principal decay modes.

^{204}Fr is known to have three isomers, 3^+, 7^+ and 10^- from earlier work.[7] In the present work, in addition to α transitions from each isomeric state, we measured the isomeric transition from the 10^- state to the 7^+ state, and can obtain a good estimate of the ec/β^+ decay rate of ^{204}Fr isomers to ^{204}Rn from the observation of known γ rays in ^{204}Rn. The population and de-population of the three different isomers in ^{200}At was used to confirm branching ratios measured in earlier work.[7]

Only two isomers, 10^- and 3^+, are known in ^{202}Fr. No isomeric transition was observed in its γ-ray decay spectrum. After α decay of each isomer to the equivalent isomer in ^{198}At, the decay chain is further traced by measurement of the αs emitted by the daughters and granddaughters. The number of α decays away from each isomer in ^{198}At is about equal to the number of decays into each isomer, indicating that the α decay branch of each isomer is essentially 100%. However, a few α decays of ^{198}Po indicate that a small fraction, ~ 2% of the ^{198}At produced, actually decays via ec/β^+ to Po. This permits the placement of a very high lower limit on the α decay branch for each of the two isomers populated in ^{198}At; the α branch is ≥ 97% for the 3^+ isomer and ≥ 94% for the 10^- isomer.

1. Abstract of published paper: *ENAM 95, International Conference on Exotic Nuclei and Atomic Masses* (Editions Frontieres, Gif-sur-Yvette, France, 1995), pp. 545-546.
2. University of Tennessee, Knoxville.
3. University of Maryland, College Park.
4. Oxford University, Oxford, United Kingdom.
5. Louisiana State University, Baton Rouge.
6. ISOLDE Collaboration, CERN, Geneva, Switzerland.
7. M. Huyse et al., *Phys. Rev. C* **46**, 1209 (1992).

NUCLEAR STRUCTURE AND ASTROPHYSICS WITH ACCELERATED BEAMS OF RADIOACTIVE IONS: A NEW MULTIDISCIPLINARY RESEARCH TOOL[1]

J. D. Garrett

After a brief discussion of the techniques for producing accelerated radioactive ion beams (RIBs), several recent scientific applications are mentioned. Three general nuclear structure topics, which can be addressed using RIBs, are discussed in some detail: possible modifications of the nuclear shell structure near the particle drip lines; various possibilities for decoupling the proton and neutron mass distributions for weakly bound nuclei; and tests of fundamental nuclear symmetries for self-conjugate and nearly self-conjugate nuclei. The use of RIBs to study r- and rp-process nucleosynthesis also is discussed.

1. Abstract of published paper: *The International Nuclear Physics Conference: Nuclear Physics - at the Frontiers of Knowledge*, eds. Z.-X. Sun and J.-C. Xu (World Scientific, 1996, Singapore), p. 595.

ACCELERATED BEAMS OF RADIOACTIVE IONS: A NEW MULTIDISCIPLINARY RESEARCH TOOL[1]

J. D. Garrett

Recent technical developments permit the production of accelerated beams of radioactive nuclei (nuclei of isotopes which do not occur terrestrially) of sufficient intensity to be utilized for a variety of scientific enterprises. These endeavors range from studies of the structure of exotic unstable nuclei, to investigations of astrophysical processes occurring in the most violent cosmic environments, and a variety of material science topics.

1. Abstract of published paper: *McGraw-Hill 1996 Yearbook of Science and Technology*, ed. Sybil P. Parker et al. (McGraw Hill, 1996, New York), p. 286-288.

WORKSHOP ON DATA ANALYSIS

H. Q. Jin,[1] *M. J. Brinkman, and W. Reviol*[1]

In February 1996, a *Workshop on Data Analysis* was hosted by the Physics Division in conjunction with the Joint Institute for Heavy Ion Research. Over fifty people from the United States, Canada, and Europe participated in all or part of the four–day–long workshop.

The *Workshop on Data Analysis* was designed to bring together both users and programmers for formal presentations, "hands–on" demonstrations, and informal discussions of various aspects of data–reduction techniques and applications used in low–energy nuclear structure experimental research. To meet this purpose, each of the four days was divided into morning and afternoon sessions, with the morning sessions focusing on formal presentations. Fourteen speakers, representing all of the major North American nuclear structure national laboratories (i.e., ORNL, ANL, LBNL, BNL, and Chalk River), provided nineteen formal presentations during the morning sessions (see Table 2.2 below). Although providing a forum to advertise existing software and demonstrate tricks, tips, and techniques on its use, the primary purpose of the formal presentations was to provide discussion topics for the afternoon sessions.

The afternoon session was divided into two parts: 1) an open "town hall" style meeting focusing on user issues and concerns arising from the morning's presentation and 2) an informal demonstration and discussion period. The "town hall" sessions covered such topics as general concerns, high–fold data analysis, data representations and data bases, and future directions for work.

A meeting of the GAMMASPHERE Software Working Group was also held in conjunction with this workshop.

Table 2.2. List of formal presentations

Presenter	Affiliation	*Presentation Title*
M. Brinkman	ORNL	*ORNL Data Analysis Software*
		Under the Hood: A Tinkerer's Summary
T. Burrows	BNL	*Nuclear Structure Data Bases and Program at the NNDC*
P. Ekstrom	Lund	*Nuclear Data on the Web*
C. Hampton	M(ich)SU	*A Search Technique for γ–ray Bands Using Segmented Fourier Analysis*
H. Jin	ORNL	*The High–Spin Data Base and Its Applications*
G. Kumbartzki	Rutgers	*XSA–Interactive Spectrum Analysis Based on XLib*
T. Lauritsen	ANL	*From the Front End to the Final Spectrum: I*
		From the Front End to the Final Spectrum: II
R. MacLeod	LBNL	*High–fold Data Compression and Storage*
B. Piercey	M(iss)SU	*The Common Histogram Object and the MADAM Implementation*
D. Radford	Chalk River	*Radware: I*
		Radware: II
		Radware: III
		Radware: IV
S. Sorensen	Tennessee	*Data Analysis at RHIC*
P. Varmette	M(iss)SU	*MADAM: A Modular Program for Data Analysis*
J. Wells	Tenn. Tech.	*Analysis of Lifetime Data*
D. Winchell	Pittsburgh	*Distributed Analysis of High–Fold Data*

1. University of Tennessee, Knoxville.

NUCLEAR REACTIONS AND ASTROPHYSICS

CRITICAL COMPARISON OF FOLDED POTENTIAL AND DEFORMED POTENTIAL MODELS OF HEAVY-ION INELASTIC SCATTERING[1]

J. R. Beene, D. J. Horen[2], and G. R. Satchler[3]

We give a comparative review of the use of the deformed potential and folded potential models for the analysis of data from the inelastic scattering of heavy ions and alpha particles. Representative cases are studied. It is shown that use of the deformed potential can very significantly underestimate the corresponding nuclear transition rate by amounts that increase strongly as the multipolarity increases. Some criticism of the implicit folding procedure is also offered.

1. Abstract of published paper: *Nucl. Phys.* **A596,** 137-154 (1996).
2. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
3. University of Tennessee, Knoxville.

FOLDED POTENTIAL ANALYSIS OF THE EXCITATION OF GIANT RESONANCES BY HEAVY IONS[1]

D. J. Horen,[2] J. R. Beene, and G. R. Satchler[3]

Measurements of the excitation of nuclear giant resonances by heavy-ion inelastic scattering have previously been analyzed using the deformed optical potential model. Here we reexamine these data using a folded potential model which employs a simple, but effective, nucleon-nucleon interaction that was deduced recently from heavy-ion elastic scattering measurements. The resulting estimates of the sum-rule exhaustion by the giant quadrupole resonance increase by amounts ranging from about 20% for the lighter targets to no change for ^{208}Pb. Applying the same model to data for excitation of the giant monopole resonance, we find that these transitions overexhaust the corresponding sum rule even more than previously indicated.

1. Abstract of published paper: *Phys. Rev. C* **52,** 1554-64 (1995).
2. Joint Institute for Heavy Ion Research, Oak Ridge, TN.
3. University of Tennessee, Knoxville.

SIMULTANEOUS MEASUREMENTS OF $(\vec{p},\vec{p}')$ AND $(\vec{p},p'\gamma)$ OBSERVABLES FOR THE 15.11 MeV, 1^+, T = 1 STATE IN ^{12}C AT 200 MeV[1]

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We have made simultaneous measurements of singles $(\vec{p},\vec{p}')$ spin-transfer observables and coincident $(\vec{p},p'\gamma)$ yields and asymmetries for the 15.11 MeV, 1^+, T = 1 state in ^{12}C, at an incident proton bombarding energy of 200 MeV. Data were taken at four proton-scattering angles ranging from $\theta_p^{c.m.} = 5.5°$ to 16.5°.

Both vertical (normal to the reaction plane) and horizontal (in-plane) incident beam polarizations were used, which allowed us to extract 16 different observables for this transition. In particular, using the $(\vec{p}, p'\gamma)$ reaction, we measured the sideways and longitudinal analyzing powers, D_{0S} and D_{0L}, which vanish identically in the $(\vec{p}, p')$ reaction. Detailed comparisions of all observables to calculations done in both relativistic and nonrelativistic formalisms are presented. Surprisingly, a relativistic description in which knock-on exchange processes are not explicitly included provides the best overall agreement with the data.

1. Abstract of published paper: *Phys. Rev. C* **52**, 2559-76 (1995).
2. Indiana University, Cyclotron Facility, Bloomington.
3. Centenary College of Louisiana, Shreveport.
4. Ohio University, Athens.

DYNAMICAL EFFECTS IN FUSION REACTIONS FORMING ^{110}Sn (Ref. 1)

M. Thoennessen,[2] E. Ramakrishnan,[2] J. R. Beene, F. E. Bertrand, M. L. Halbert, D. J. Horen, P. E. Mueller, and R. L. Varner

High-energy γ-ray spectra were measured following the reactions ^{18}O + ^{92}Mo and ^{50}Ti + ^{60}Ni forming the compound nucleus ^{110}Sn at the same excitation energy of 56 MeV. The angular momentum gated γ-ray spectra from both reactions can be described by standard statistical model calculations. The influence of particle and γ-ray decay during the formation time is found to be small in both reactions. This result is consistent with predictions from dissipative dynamics calculations.

1. Abstract of published paper: *Phys. Rev. C* **51**, 3148 (1995).
2. Michigan State University, NSCL, East Lansing.

GIANT DIPOLE RESONANCE IN EXCITED ^{120}Sn AND ^{208}Pb NUCLEI POPULATED BY INELASTIC ALPHA SCATTERING[1]

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The evolution of the giant dipole resonance (GDR) in hot ^{120}Sn and ^{208}Pb nuclei was studied by measuring high-energy γ rays from the decay of the resonance. The excited nuclei were populated by inelastic scattering of α-particles at 40 and 50 MeV/nucleon. The resonance width was observed to increase systematically with excitation energy in both systems. Inelastic scattering populates low-angular momentum states in the target. The observed width increase is thus attributed to fluctuations in the nuclear shape induced by temperature.

1. Abstract of published paper: *Nucl. Phys.* **A599**, 49c-56c. (1996).
2. Michigan State University, NSCL, East Lansing.
3. Washington University, St. Louis, MO.

A FIRST LOOK AT THE ^{84}Kr (1260 MeV) + ^{27}Al DATA USING THE HEAVY ION LIGHT ION DETECTOR[1]

H. Madani,[2] E. Chávez-Lomelí,[2] A. Dacal,[2] M. E. Ortiz,[2] J. Suro,[2]
J. Gomez del Campo, J. W. McConnell, and D. Shapira

Evaporation residues obtained with the 1260-MeV ^{84}Kr + ^{27}Al reaction were measured in coincidence with light particles (protons and alphas), using the HILI detector array. The energy spectra of the evaporation residues and light particles in coincidence are compared to the predictions of the statistical decay code LILITA. Data on intermediate mass fragments which are abundantly produced in this reaction are also reported, and compared to a modified version of LILITA.

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1. Abstract of published paper: *Revista Mexicana de Física* **42**, Suplemento 1, 188-197 (1996).
2. Instituto de Física, Universidad Nacional Autónoma de México, México.

LIGHT PARTICLE-EVAPORATION RESIDUE COINCIDENCES FOR THE ^{79}Br + ^{27}Al SYSTEM AT 11.8 MeV/NUCLEON[1]

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Evaporation residues (ER) of Z = 34-43 are measured in singles and in coincidence with emitted protons, deuterons, tritons, and alpha particles. Measurements are done with a large detector array that covers the scattering angles from 2.5° to 25°. The energy centroids of the coincidence spectra of the protons are reasonably well described by statistical model calculations assuming complete fusion, although those for the deuterons and tritons are not. The α-particle spectra are significantly different than the calculated ones. The slopes of the high-energy spectra of the protons required a level density paramenter a > A/12. Comparisons between the experimental ER singles spectra and complete fusion calculations show small deviations that can be explained by incomplete fusion; however, when analyzed in coincidence with light particles a very good description with complete fusion is found, especially if the emission of intermediate mass fragments is included in the calculations.

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1. Abstract of published paper: *Phys. Rev C* **53**, 222 (1996).
2. Argonne National Laboratory, Argonne, IL.
3. University of Maryland, College Park.
4. Grand Accelerateur National d'Ions Lourds, Caen, France.
5. Instituto de Fisica, Universidad Nacional Autonoma de Mexico, Mexico.
6. DAPNIA/SPhN CEN-Saclay, Gif-sur-Yvette, France.
7. Universitá degli Studi di Salerno, Salerno, and INFN-Salerno, Italy.

COINCIDENCES BETWEEN LIGHT PARTICLES, EVAPORATION RESIDUES AND COMPLEX FRAGMENTS EMITTED IN THE REACTION ^{58}Ni + ^{58}Ni AT 500 MeV BOMBARDING ENERGY[1]

J. Gomez del Campo, D. Shapira, E. Chavez,[2] M.E. Ortiz,[2] A. Dacal,[2] A. D'Onofrio,[3] and F. Terrasi[4]

Light particles (protons and alphas) were measured in coincidences with complex fragments $(4 < Z < 10)$ and evaporation residues $(Z > 40)$ using the large detector array HILI. A ^{58}Ni beam of 500 MeV extracted from the HHIRF tandem accelerator was used to bombard a ^{58}Ni target of 99% enrichment. A good account of the proton and alpha spectra in coincidences with the residues can be achieved only by including in the statistical model calculation the emission of complex fragments and allowing a small emission of a dinuclear configuration formed prior to fusion. The relative kinetic energy spectra between the complex fragments and the residues show a typical coulomb peak consistent with emission from the compound nucleus, and the out-of-plane angular correlation shows that the emission is coplanar.

1. Abstract of published paper: *Revista Mexicana de Fisica* **42**, Suplemento 1, 101-116 (1996).
2. Instituto de Fisica, Universidad Nacional Autonoma de Mexico, Mexico.
3. Universitá degli Studi di Salerno, Salerno, and INFN-Salerno, Italy.
4. Seconda Universitá di Naopli and INFN-Napoli, Italy.

DECAY OF ^{160}Er IN ^{16}O + ^{144}Nd AND ^{64}Ni + ^{96}Zr FUSION REACTIONS[1]

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The population of evaporation residue entry states in the decay of the compound nucleus ^{160}Er*(54 MeV) is investigated in a cross-bombardment employing the reactions ^{16}O + ^{144}Nd and ^{64}Ni + ^{96}Zr. Evaporation residue cross sections and entry state γ-ray fold distributions of the dominant exit channels were obtained for each reaction, using a 4π γ-ray detection system. An entrance-channel dependence of the γ-ray fold distributions of the *xn* products is observed. This effect is described successfully by the statistical model making use of compound nucleus angular momentum distributions obtained with a fusion model that provides a good description of the bombarding energy dependence of fusion data for both reactions. In accordance with recent findings on the decay of ^{164}Yb*, it is suggested than the observed differences in the population of the dominant exit channels originate from the primary spin distributions rather that a possible dependence of the compound nucleus decay on the formation mode.

1. Abstract of published paper: *Phys. Rev. C* **51**, 2584-92 (1995).
2. Washington University, St. Louis, MO.
3. Michigan State University, East Lansing.

MASS AND CHARGE DISTRIBUTIONS FOR THE REACTION ^{40}Ca + ^{209}Bi AT 600 MeV[1]

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The charge and mass of the projectile-like fragments produced in the 15-MeV per nucleon ^{40}Ca + ^{209}Bi reaction were determined for products detected near the grazing angle. Neutron number-charge (*N-Z*) distributions were generated as a function of the total kinetic energy loss and parametrized by their centroids, variances, and correlation coefficients. Although the initial system is very asymmetric, after the interaction, a drift of the charge and mass centroids toward further asymmetry is observed. The production of projectile-like fragments is consistent with a tendency of the projectile-like fragments to retain the projectile neutron-to-proton ratio $\langle N \rangle / \langle Z \rangle \simeq 1$. The correlation coefficient remains well below 1.0 for the entire range of total kinetic energy lost. Predictions of two nucleon exchange models, Randrup's and Tassan-Got's, are compared to the experimental results. The models are not able to reproduce the evolution of the experimental distributions, especially the fact that the variances reach a maximum and then decrease as function of the energy loss. This behavior supports the hypothesis that some form of projectile-like fragmentation or cluster emission is perturbing the product distribution from that expected from a damped mechanism.

1. Abstract of published paper: *Phys. Rev. C* **52**, 3114 (1995).
2. University of Maryland, College Park.

NEW MEASUREMENT OF THE CHARGE RADIUS OF THE NEUTRON[1]

S. Kopecky,[2] P. Riehs,[2] J. A. Harvey, and N. W. Hill

The neutron transmission through a thorogenic liquid ^{208}Pb sample 2 in. thick has been measured in the neutron energy range between 0.1 and 360 eV at the ORNL neutron source ORELA. Analyzing the shape of the transmission spectra as a function of neutron energy, agreement was found with the predictions by the atomic form factor. With a sensitivity for the mean squared charge radius of the neutron r_n^2 as high as 3%, a very reliable and also accurate result of r_n^2 r_n = -0.113 ± 0.003 ±0.004 fm^2 was extracted. For the neutron-electron scattering length we obtained b_{ne}= (-1.31 ± 0.03 ± 0.04) X 10^{-3} fm.

1. Abstract of published paper: *Phys. Rev. Lett.* **74**, 2427 (1995).
2. Institut für Kemphysik der Technischen Universität Wien, Wien, Austria.

MEASUREMENT OF THE $^{17}O(p,a)^{14}$ N CROSS SECTION AT STELLAR ENERGIES[1]

J. C. Blackmon,[2] A. E. Champagne,[2] M. A. Hofstee,[2] M. S. Smith, R. C. Downing,[3] and C. P. Lamaze[3]

The cross section for the astrophysically important $^{17}O(p,a)^{14}N$ reaction was measured at proton energies of 75 and 65 keV. Thick, high-purity $Ta_2 0_5$ targets (77% enriched $^{17}0$) and large-area detectors were used with beam currents of 0.45 mA. Backgrounds were measured using $Ta_2 0_5$ targets of natural isotopic composition. The expected resonance at E_p = 70 keV was observed in the data taken at 75 keV, and its proton width was found to be $22 \pm 3_{stat} \pm 2_{target}\, {}^{+2}_{-1}{}_{beam}$ meV.

1. Abstract of published paper: *Phys. Rev. Lett.* **74**, 2642 (1995).
2. University of North Carolina at Chapel Hill, and Triangle Universities Nuclear Laboratory, Durham, NC.
3. National Institute of Standards and Technology, Gaithersburg, MD.

MEASUREMENT OF $^{7}Li(n,\gamma_0)^{8}Li$ CROSS SECTIONS AT E_n = 1.5–1340 eV (Ref. 1)

J. C. Blackmon,[2] A. E. Champagne,[2] J. K. Dickens, J. A. Harvey, M. A. Hofstee,[2] S. Kopecky,[3] D. C. Larson, D. C. Powell,[2] S. Raman, and M. S. Smith

The $^{7}Li(n,\gamma)^{8}Li$ cross section is important in inhomogeneous big bang models, and as a constraint on model parameters used to determine the solar $^{7}Be(p,\gamma)^{8}B$ reaction rate. Values of the $^{7}Li(n,\gamma_0)^{8}Li$ reaction cross section were measured for neutron energies between 1.5 and 1340 eV at the Oak Ridge Electron Linear Accelerator. The normalization of the cross section was determined by measuring the gamma-ray yield from the $^{7}Li(n,\gamma_0)^{8}Li$ reaction relative to that from the $^{10}B(n,\alpha\gamma)^{7}Li$ reaction. The cross section was found to have the inverse neutron-velocity relationship $(1/v)$ indicative of *s*-wave capture. These results help resolve ambiguities in previous measurements.

1. Abstract of published paper: *Phys. Rev. C* **54**, 383 (1996).
2. University of North Carolina at Chapel Hill, and Triangle Universities Nuclear Laboratory, Durham, NC.
3. Institut für Kernphysik der Technischen Universität Wien, Wien, Austria.

INVESTIGATING THE ASTROPHYSICALLY IMPORTANT E_x = 2.646 MeV STATE IN ^{20}Na (Ref. 1)

M. A. Hofstee,[2] J. C. Blackmon ,[2] A. E. Champagne,[2] N. P. T. Bateman,[3] P. D. Parker,[3] K. Yildiz,[3] B. M. Young,[3] R. B. Vogelaar,[4] M. S. Smith, and A. J. Howard[5]

Observations of neon lines in the spectra of energetic novae have prompted a renewed look at explosive hydrogen burning. The $^{19}Ne(p,\gamma)^{20}Na$ reaction is expected to play a major role in the breakout of the hot CNO cycle to the rp-process which can process CNO nuclei to heavier elements. The reaction rate is dominated by the lowest resonance in the ^{19}Ne + p system, corresponding to the E_x = 2.646 MeV state in ^{20}Na. A large variety of nuclear experimental techniques have been used to study this state, e.g., charge exchange reactions, β-delayed proton decay, and radioactive beams. Their results have lead to a J^{π}= 3 + assignment for this state [B. Brown et al., Phys. Rev. C 48 (1993)1456], allowing an estimate of the proton width (Γ_p). This leaves the gamma width (Γ_γ)to be determined. We have performed $^{20}Ne(^{3}He, t\gamma)$ experiments to measure the branching ratio (Γ_γ/Γ) of the E_x = 2.646 MeV excited state in ^{20}Na.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res.* B **99**, 346 (1995).
2. University of North Carolina at Chapel Hill, and Duke University, Durham, NC.
3. Yale University, New Haven, CT.
4. Princeton University, Princeton, NJ.
5. Trinity College, Hartford, CT.

STELLAR NEUTRON CAPTURE CROSS SECTIONS OF THE TIN ISOTOPES[1]

K. Wisshak,[2] F. Voss,[2] Ch. Theis,[2] F. Käppeler,[2] K. Guber,[3] L. Kazakov,[4] N. Kornilov,[4] and O. Reffo[5]

The neutron capture cross sections of ^{114}Sn, ^{115}Sn, ^{116}Sn, ^{117}Sn, ^{118}Sn, and ^{120}Sn were measured in the energy range from 3 to 225 keV at the Karlsruhe 3.75 MV Van de Graaff accelerator. Neutrons were produced via the ^{7}Li$(p,n)^7$ Be reaction using a pulsed proton beam. Capture events were registered with the Karlsruhe 4π barium fluoride detector. The experiment was complicated by the small *(n,y)* cross sections of the proton magic tin isotopes and by the comparably low enrichment of the rare isotopes ^{114}Sn and ^{115}Sn. Despite significant corrections for capture of scattered neutrons and for isotopic impurities, the high efficiency and the spectroscopic quality of the BaF_2 detector allowed the determination of the cross-section ratios with overall uncertainties of 1-2%, five times smaller compared to existing data. Based on these results, Maxwellian-averaged *(n,y)* cross sections were calculated for thermal energies between $kT=10$ and 100 keV. These data are used for a discussion of the solar tin abundance and for an improved determination of the isotopic *s*- and *r*-process components. [S0556-2813(96)01509-9]

1. Abstract of published paper: *Phys. Rev. C* **54**, 1451 (1996).
2. Forschungszentrum Karlsruhe, Institut für Kernphysik, Karlsruhe, Germany.
3. University of Tennessee, Knoxville.
4. Institute for Physics and Power Engineering, Obninsk, Kaluga Region, Russia.
5. Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energia Alternative, Centro Dati Nucleari, Bologna, Italy.

NEUTRON RESONANCE SPECTROSCOPY ON ^{113}Cd TO E_n=15 keV (Ref. 1)

C. M. Frankle,[2] E. I. Sharapov,[3] Yu. P. Popov,[3] J. A. Harvey, N. W. Hill, and L. W. Weston

The results of a study of the compound nucleus ^{114}Cd by neutron time-of-flight spectroscopy methods are presented. Targets of both natural cadmium and cadmium enriched in the 113 isotope were used. The neutron total capture and neutron transmission were both measured. A total of 275 new resonances were located. In addition, 102 other resonances which were previously known but not assigned to a particular cadmium isotope were definitively assigned to ^{113}Cd. Resonance parameters E_0 and $g\Gamma_n$ were obtained for both newly identified and previously known resonances. Of the 437 resonances now known in ^{113}Cd, we identify 104 of them as $\ell = 1$ based on their small widths. Strength functions and level spacings are obtained for both $\ell = 0$ and $\ell = 1$ resonances. Comparisons of the data with Porter-Thomas reduced-width distributions, Wigner nearest-neighbor spacing distributions, and the Dyson-Metha Δ_3 statistic are given. The linear correlation coefficient between adjacent spacings is also discussed. The spectroscopic information obtained is of importance for planning and interpretation of parity violation measurements on the *p*-wave resonances of ^{113}Cd.

1. Abstract of published paper: *Phys. Rev. C* **50**, 2774 (1994).
2. Los Alamos National Laboratory, Los Alamos, NM.
3. Joint Institute for Nuclear Research, Dubna, Russia.

RESONANCE NEUTRON CAPTURE AND TRANSMISSION MEASUREMENTS AND THE STELLAR NEUTRON CAPTURE CROSS SECTIONS OF ^{134}Ba AND ^{136}Ba (Ref. 1)

P. E. Koehler, R. R. Spencer, R. R. Winters,[2] K. H. Guber,[3] J. A. Harvey, N. W. Hill, and M. S. Smith

We have made high-resolution neutron capture and transmission measurements on isotopically enriched samples of ^{134}Ba and ^{136}Ba at the Oak Ridge Electron Linear Accelerator (ORELA) in the energy range from 20 eV to 500 keV. Previous measurements had a lower energy limit of 3 - 5 keV, which is too high to determine accurately the Maxwellian-averaged capture cross section at the low temperatures (kT ≈8 - 12 keV) favored by the most recent stellar models of the *s*-process. Our results for the astrophysical reaction rates are in good agreement with the most recent previous measurement at the classical *s*-process temperature, kT = 30 keV, but show significant differences at lower temperatures. We determined that these differences were due to the effect of resonances below the energy range of previous experiments and to the use of incorrect neutron widths in a previous resonance analysis. Our data show that the ratio of reaction rates for these two isotopes depends more strongly on temperature than previous measurements indicated. One result of this temperature dependence is that the mean *s*-process temperature we derived from a classical analysis of the branching at ^{134}Cs is too low to be consistent with the temperature derived from other branching points. This inconsistency is evidence for the need for more sophisticated models of the *s*-process beyond the classical model. We used a reaction network code to explore the changes in the calculated isotopic abundances resulting from our new reaction rates for an s-process scenario based on a stellar model. These calculations indicate that the previously observed 20% discrepancy with respect to the solar barium abundance is reduced but not resolved by our new reaction rates.

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1. Abstract of published paper: *Phys. Rev. C* **54**, 1463 (1996).
2. Denison University, Granville, OH.
3. University of Tennessee, Knoxville.

NEW (n,γ) AND TOTAL CROSS SECTION MEASUREMENTS FOR ^{134,136}Ba AND THEIR IMPACT ON *s*-PROCESS NUCLEOSYNTHESIS CALCULATIONS[1]

P. E. Koehler, R. R. Spencer, R. R. Winters,[2] K. H. Guber, J. A. Harvey, and N. W. Hill

We have measured the total and (n,γ) cross sections for ^{134,136}Ba with the recently improved experimental facilities at the Oak Ridge Electron Linear Accelerator (ORELA). The isotopes of barium play a vital role in *s*-process nucleosynthesis, hence an accurate determination of their (n,γ) cross sections is very important for a better understanding of the s-process. The two previous ^{134,136}Ba(n,γ) measurements[3,4] did not extend to low enough neutron energies to reliably obtain the astrophysical reaction rate at the low temperatures (kT ≈ 8 - 12 keV) favored by the most recent stellar models[5,6] of the *s*-process. In addition, high-quality neutron total cross section data, which did not exist before our measurements, can be indispensable for minimizing systematic uncertainties in the reduction of the raw (n,γ) data to astrophysical reaction rates. The reaction rates obtained from our data are in good agreement with the most recent measurements[3] at kT = 30 keV, but differ significantly at lower temperatures. Also, our data indicate that the ratio of reaction rates for these two isotopes depends more strongly on temperature than previously thought, hence, previous estimates of the *s*-process temperature[3] which assumed that this ratio does not depend on temperature may be in error. In previous calculations[3] based on a model[5] of nucleosynthesis occurring in low-mass stars at kT ≈ 12 keV, the $^{134,136}Ba$ isotopes were overproduced relative to other *s*-process normalization points. We are using the *s*-process reaction network code NETZ[7] to investigate the effect of the changes in the reaction rates at low temperatures indicated by our new results. Our initial calculations indicate that in the 12 keV model, the overproduction is slightly reduced for ^{136}Ba but is increased for ^{136}Ba, and that the overproduction of ^{134}Ba is even greater in the most recent *s*-process model[6] where nucleosynthesis occurs in a radiative environment at kT ≈ 8 keV.

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1. Abstract of published paper: Proceedings of the Fourth Conference on Nuclei in the Cosmos, Notre Dame, IN, June 20-27, 1996.
2. Denison University, Granville, OH.
3. F. Voss et al., *Phys. Rev. C* **50**, 2582 (1994); F. Voss et al., *Phys. Rev. C* **52**, 1102 (1995).
4. A. Musgrove et al., *Nucl. Phys.* **A256**, 173 (1976).
5. R. Gallino et al., *Astrophys. J.* **410**, 400 (1993).
6. O. Straniero et al., *Astrophys. J.* **440**, L85 (1995).
7. S. Jaag, private communication.

NEW NEUTRON CAPTURE AND TRANSMISSION MEASUREMENTS FOR $^{134,136}Ba$ AT ORELA AND THEIR IMPACT ON *s*-PROCESS NUCLEOSYNTHESIS CALCULATIONS[1]

P. E. Koehler, R. R. Spencer, R. R. Winters,[2] K. H. Guber,[3] J. A. Harvey, N. W. Hill, and M. S. Smith

We have made high-resolution neutron capture and transmission measurements on isotopically enriched samples of ^{134}Ba and ^{136}Ba at the Oak Ridge Electron Linear Accelerator (ORELA) in the energy range from 20 eV to 500 keV. Previous measurements had a lower energy limit of 3 - 5 keV, which is too high to determine accurately the Maxwellian-averaged capture cross section at the low temperatures (kT ≈ 6 - 12 keV) favored by the most recent stellar models of the *s*-process. Our results for the astrophysical reaction rates are in good agreement with the most recent previous measurement at the classical *s*-process temperature, kT = 30 keV, but show significant differences at lower temperatures. We discuss the astrophysical implications of these differences.

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1. Abstract of published paper: Proceedings of the Fourth Conference on Nuclei in the Cosmos, Notre Dame, IN, June 20-27, 1996.
2. Denison University, Granville, OH.
3. University of Tennessee, Knoxville.

THE STELLAR (n,γ) CROSS SECTIONS OF THE UNSTABLE ^{135}Cs (Ref. 1)

S. Jaag,[2] F. Käppeler,[2] and P. Koehler

The (n,γ) cross sections of the unstable isotope ^{135}Cs has been measured relative to that of gold by means of the activation method. The sample was produced by ion implantation in a high resolution mass separator and irradiated in a quasi-stellar neutron spectrum for kT = 25 keV using the $^{7}Li(p,n)^{7}Be$ reaction near threshold. The ≈8 uncertainty of the resulting stellar cross sections is dominated by the thermal (n,γ) cross section used for sample definition.

1. Abstract of published paper: *Proceedings of the Fourth Conference on Nuclei in the Cosmos*, Notre Dame, IN, June 20-27, 1996.

2. Forschungszentrum Karlsruhe, Karlsruhe, Germany.

MEASUREMENTS OF ^{142,144}Nd(n,γ) CROSS SECTIONS AT ORELA FOR ASTROPHYSICAL s-PROCESS STUDIES[1]

K. H. Guber,[2] R. R. Spencer, P. E. Koehler, and R. R. Winters[3]

We have completed measurements of the ^{142,144}Nd (n,γ) cross sections from approximately 20 eV to 200 keV at the Oak Ridge Electron Linear Accelerator (ORELA) using a recently improved C_6D_6 detector apparatus. ^{142}Nd is an s-only isotope, i.e., it is only formed during the s-process. It has a closed neutron shell and therefore defines a step in the $<\sigma>N_s$ curve from which the mean s-process neutron exposure can be calculated. In addition, ^{144}Nd is the normalization point for the neodymium abundances. Also, accurate (n,γ) cross sections would help to determine the r- and s-process residuals of these isotopes and will impact the interpretation of the recently discovered isotopic anomalies in silicon carbide grains from the Murchison meteorite. Our new (n,γ) cross sections also show that reaction rate extrapolations for nuclei near closed neutron shells from measured values at 30 keV down to 8 keV can be inaccurate.

1. Abstract of published paper: *Proceedings of the Fourth Conference on Nuclei in the Cosmos*, Notre Dame, IN, June 20-27, 1996.

2. University of Tennessee, Knoxville.

3. Denison University, Granville, OH.

STELLAR NEUTRON CAPTURE CROSS SECTIONS OF THE TIN ISOTOPES[1]

K. Wisshak,[2] F. Voss,[2] Ch. Theis,[2] F. Käppeler,[2] K. Guber,[3] L. Kazakov,[4] N. Kornilov,[4] and O. Reffo[5]

The neutron capture cross sections of ^{114}Sn, ^{115}Sn, ^{116}Sn, ^{117}Sn, ^{118}Sn, and ^{120}Sn were measured in the energy range from 3 to 225 keV at the Karlsruhe 3.75 MV Van de Graaff accelerator. Neutrons were produced via the ^{7}Li(p,n)^7 Be reaction using a pulsed proton beam. Capture events were registered with the Karisruhe 4π barium fluoride detector. The experiment was complicated by the small *(n,y)* cross sections of the proton magic tin isotopes and by the comparably low enrichment of the rare isotopes ^{114}Sn and ^{115}Sn. Despite significant corrections for capture of scattered neutrons and for isotopic impurities, the high efficiency and the spectroscopic quality of the BaF_2 detector allowed the determination of the cross-section ratios with overall uncertainties of 1-2%, five times smaller compared to existing data. Based on these results, Maxwellian-averaged *(n,y)* cross sections were calculated for thermal energies between kT = 10 and 100 keV. These data are used for a discussion of the solar tin abundance and for an improved determination of the isotopic s- and r-process components. [S0556-2813(96)01509-9]

1. Abstract of published paper: *Phys. Rev. C* **54**, 1451 (1996).
2. Forschungszentrum Karlsruhe, Institut für Kernphysik, Karlsruhe, Germany.
3. Institute for Physics and Power Engineering, Obninsk, Kaluga Region, Russia.
4. Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energia Alternative, Centro Dati Nucleari, Bologna, Italy.
5. University of Tennessee, Knoxville.

FISSION CROSS-SECTION MEASUREMENTS OF THE ODD-ODD ISOTOPES ^{232}Pa, ^{238}Np, AND ^{236}Np (Ref. 1)

Y. Danon,[2] M. S. Moore,[3] P. E. Koehler,[3] P. E. Littleton,[3] G. G. Miller,[3] M. A. Ott,[3] L. J. Rowton,[3] W. A. Taylor,[3] J. B. Wilhelmy,[3] M. A. Yates,[3] A. D. Carlson,[4] N. W. Hill, R. Harper,[5] and R. Hilko[5]

Transmutation of actinide waste into fission products could be enhanced by using resonance fission of odd-odd target materials; those of interest are ^{232}Pa, ^{238}Np, and ^{242}Am. Fission cross-section measurements of two of these short-lived materials were performed at Los Alamos National Laboratory. Samples were produced by the *(d,2n)* reaction in the Los Alamos Ion Beam Facility followed by fast radiochemistry to separate the odd-odd target of interest. The fission cross section of the nanogram samples was measured in a high intensity pulsed neutron beam produced by 800-MeV proton spallation. Using this procedure, the fission cross sections of the 1.3-day ^{232}Pa and 2.1-day ^{238}Np were successfully measured in the energy range from 0.01 eV 50 keV. The fission cross section of the relatively long-life isotope ^{236}Np was also measured in the same system while the short half-life isotopes were being prepared. The results and resonance analysis are presented.

1. Abstract of paper to be published in *Nuclear Science and Engineering.*
2. Rensselaer Polytechnic Institute, Troy, NY.
3. Los Alamos National Laboratory, Los Alamos, NM.
4. National Institute for Standards and Technology, Gaithersburg, MD.
5. EG&G Energy Measurements, Los Alamos, NM.

INTERMEDIATE STRUCTURE IN THE NEUTRON-INDUCED FISSION CROSS SECTION OF ^{236}U (Ref. 1)

W. E. Parker,[2] J. Eric Lynn,[2] G. L. Morgan,[2] P. W. Lisowski,[2] A, D. Carlson,[3] and N. W. Hill

Neutron-induced fission of ^{236}U has been measured at the Los Alamos Neutron Scattering Center with a white neutron source using a fast parallel plate ionization chamber at a flight path of ~56 m. In the resonance and the intermediate resonance region, very little of the previously reported structure was detected. Only five resonance structures were observed. Additionally, the width of the 5.45 eV resonance is approximately 100 times smaller than previously reported. An explanation for the discrepancies between old data and data reported here is discussed. New fission widths for resonances from 5.45 eV to 10.4 keV are reported. The new data are in agreement with theoretical estimates.

1. Abstract of published paper: *Phys. Rev. C* **49**, 672 (1994).
2. Los Alamos National Laboratory, Los Alamos, NM.
3. National Institute of Standards and Technology, Gaithersburg, MD.

NUCLEAR ASTROPHYSICS AT THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

M. S. Smith

The potential for understanding spectacular stellar explosions such as novae, supernovae, and X-ray bursts will be greatly enhanced by the availability of the low-energy, high-intensity, accelerated beams of proton-rich radioactive nuclei currently being developed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. These beams will be utilized in absolute cross section measurements of crucial (p,γ) capture reactions in efforts to resolve the substantial qualitative uncertainties in current models of explosive stellar hydrogen burning outbursts. Details of the nuclear astrophysics research program with unique HRIBF radioactive beams and a dedicated experimental endstation - centered on the Daresbury Recoil Separator - will be presented.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res.* B **99,** 349 (1995).

NUCLEAR ASTROPHYSICS AT THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY[1]

J. C. Blackmon[2]

Reactions involving radioactive nuclei play an important role in explosive stellar events such as novae, supernovae, and X-ray bursts. The development of accelerated, proton-rich radioactive ion beams provides a tool for directly studying many of the reactions that fuel explosive hydrogen burning. The experimental nuclear astrophysics program at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory is centered on absolute cross section measurements of these reactions with radioactive ion beams. Beams of ^{17}F and ^{18}F, important nuclei in the hot-CNO cycle, are currently under development at HRIBF. Progress in the production of intense radioactive fluorine beams is reported. The Daresbury Recoil Separator (DRS) has been installed at HRIBF as the primary experimental station for nuclear astrophysics experiments. The DRS will be used to measure reactions in inverse kinematics with the techniques of direct recoil detection, delayed activity recoil detection, and recoil-gamma coincidence measurements. The first astrophysics experiments to be performed at HRIBF, and the application of the recoil separator in these measurements, are discussed.

1. Abstract of paper submitted to the 14th International Conference on the Applications of Accelerators in Research and Industry, Denton, TX.
2. University of North Carolina at Chapel Hill, NC.

FIRST ON-LINE RESULTS FOR As AND F BEAMS FROM HRIBF TARGET/ION SOURCES[1]

H. K. Carter,[2] J. Kormicki,[2] D. W. Stracener, J. B. Breitenbach,[2] J. C. Blackmon,[3] M. S. Smith, and D. W. Bardayan[4]

The first on-line tests of the ion sources to provide radioactive ion beams of ^{69,70}As and ^{17,18}F for the Holifield Radioactive Ion Beam Facility have been performed using the UNISOR facility at HRIBF. For ^{70}As the measured efficiency is 0.8 ± 0.3% with a hold-up time of 3.6 ± 0.3 hours as measured with ^{72}As at a target temperature of 1270°C. For ^{17}F the efficiency for Al^{17}F is 0.0024 ± 0.0008% with a hold-up time of 16.4 ± 0.8 m as measured with Al^{18}F at a target temperature of 1470°C.

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1. Abstract of published paper: 13th International Conference on Electromagnetic Isotope Separators and Techniques Related to Their Applications (EMIS-13), Bad Durkheim, Germany, September 22-27, 1996.
2. Oak Ridge Institute for Science and Education, Oak Ridge, TN.
3. University of North Carolina at Chapel Hill, NC.
4. Yale University, New Haven, CT.

TWO DETECTORS FOR (n,p) AND (n,α) MEASUREMENTS AT WHITE NEUTRON SOURCES[1]

P. E. Koehler,[2] J. A. Harvey, and N. W. Hill

We have developed two detectors for (n,p) and (n,α) cross section measurements at white neutron sources which make possible large increases in the sample size and geometric efficiency while at the same time reducing the potentially large background associated with the "gamma flash" to manageable levels. We present measurements of two (n,α) cross sections made with these detectors to energies as high as a few MeV.

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1. Abstract published paper: *Nucl. Instrum. Methods Phys. Res.* A **361**, 270 (1995).
2. Los Alamos National Laboratory, Los Alamos, NM.

3. HIGH-ENERGY NUCLEAR PHYSICS

OVERVIEW

The two primary and related activities of this section of the Physics Division are the WA98 experiment at CERN and the construction of the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL). The ORNL High-Energy (nuclear) Reactions Group (HERG) plays key roles in both of these large collaborative ventures, and HERG staff members are in leadership positions in both experiments. Terry Awes was designated Spokesman of WA98 in September 1996, replacing Hans Gutbrod, who has been the Spokesman of the "WA" series of heavy-ion CERN experiments (WA80, WA93, and WA98) for more than a decade since their inception. In PHENIX, the project management role of Glenn Young was changed from Deputy Project Director to Deputy Spokesman. Glenn continues to have responsibility for all PHENIX "on-line" systems, including front-end electronics, trigger, and on-line computing.

This reporting period represents the peak of activity for the WA98 experiment. Two of the three heavy-ion (lead beam) runs took place in late 1994 and 1995, respectively; the proton reference-data run took place in the spring 1996; and the third and final run was performed in October-November 1996, just beyond the range of this report. The first (1994) run of WA98 turned out to be a combination of subsystem commissioning and of production data-taking. The 1995 run (November-December) was very productive, and the data appear to be of high quality. Analysis activities are in full swing. Following the 1995 run, efforts focused on the implementation of a second tracking arm. With two tracking arms it is possible, in principle, to measure phi mesons via their kaon decay products. The second arm was fully commissioned during the 1996 run. The commissioning of the second arm was also important for PHENIX prototype and "checkout" activities. The "pad-chambers" of the second arm are PHENIX prototypes, and the time-of-flight system will be transported to PHENIX, along with the Kurchatov-Muenster-ORNL 10,000-module lead-glass detector commissioned in 1994.

The acceleration of PHENIX activities continued, and increasing resources of the section are being dedicated to this effort. Under the leadership of Ken Read, ORNL is in charge of the entire muon identifier subsystem as well as of the front-end electronics of the muon tracking system. Close collaboration continues with the Instrumentation and Controls Division on a number of PHENIX front-end electronics projects. ORNL staff members are also involved in the lead-glass portion of the electromagnetic calorimeter which, as mentioned above, will be moved from CERN and reinstalled in PHENIX. The large number of ORNL responsibilities in PHENIX have placed a considerable strain on the manpower resources of the section. The muon identifier project, which has reached the stage of construction of a full-scale prototype, was particularly hard-hit due to retirements. Staff replacements are now nearly fully in place, and the effort has been further strengthened via the allocation of additional manpower.

During this reporting period a new Laboratory-Directed Research and Development (LDRD) project was initiated in collaboration with the University of Tennessee (UT) under the leadership of Yuri Kamyshkov. Its purpose was the design of an experiment to search for possible spontaneous neutron-antineutron transitions in beams of cold neutrons produced by the proposed Advanced Neutron Source (ANS). Following the demise of the ANS project, possibilities of implementation at the proposed National Spallation Neutron Source and at the High Flux Isotope Reactor (HFIR) were studied. Since ORNL management considered various options of HFIR upgrades during the course of 1995 and 1996, the optimization of the proposed neutron oscillation experiment at the HFIR had to deal with a "moving target" situation. Consequently, at the end of fiscal year 1996, a site-specific experimental proposal was not finalized. Further ORNL LDRD funding to complete the proposal was not made available, and the effort will be pursued by UT in the future. An earlier LDRD project exploring the possibility of the use of quartz fibers in highly radiation-resistant calorimeters was completed in fiscal year 1995.

Overall, during this reporting period, the High-Energy Experimental Physics Section has continued to undergo a process of consolidation. This process began in 1994 with the cancellation of the Superconducting Super Collider (SSC) project and continued to be driven, in part, by a number of retirements and by decreasing availability of LDRD funds. The net result is that, after nearly four decades of fruitful activity carried on in close collaboration with the Physics Department of the University of Tennessee, the ORNL Physics Division is no longer involved in high-energy particle-physics research.

RELATIVISTIC HEAVY-ION COLLISIONS

CERN WA98 EXPERIMENT

WA98 Collaboration
U. of Geneva, GSI Darmstadt, U. of Jammu, JINR Dubna, Kurchatov Inst. Moscow, KVI Groningen, U. of Lund, MIT, U. of Muenster, ORNL, U. of Punjab, U. of Rajastan, U. of Tennessee, U. of Utrecht, VECC Calcutta

ORNL Collaborators: T. C. Awes (WA98 Spokesman), H. J. Kim, F. E. Obenshain, F. Plasil, S. Saini, S. P. Sorensen, P. W. Stankus, G. R. Young

During this reporting period WA98 activities were at their peak. The first two runs utilizing beams of 160-GeV/nucleon lead ions were carried out in the fall of 1994 and of 1995. The third and final heavy-ion run was completed at the time of the writing of this report, in November 1996. The experimental arrangement is shown in Fig. 3.1. ORNL, together with the University of Tennessee, continued to be responsible for the MIRAC calorimeter, which served as the primary trigger and event-characterization detector of WA98. ORNL was also responsible for the application-specific integrated-circuit (ASIC) front-end electronics of the 10,000-module lead-glass calorimeter.

The 1994 run of WA98 was a combined detector-commissioning and data-taking run, while the 1995 run was a very successful production run. Preliminary results have been presented at several conferences, and final papers are in preparation. Following the 1995 run, efforts were focused on the implementation of a second charged-particle tracking arm. The scientific motivation for operating two tracking arms in coincidence was the measurement of phi mesons via their decay into two kaons. The new tracking arm consisted of two pad-chambers, two streamer-tube chambers, and a second time-of-flight (TOF) system. It was fully commissioned during the 1996 run.

Several PHENIX prototyping activities were carried out in the framework of the WA98 experiment, including ASIC electronic systems designed for the lead-glass detector, for the second TOF, and for the pad chambers. In addition, the entire lead-glass array as well as the second TOF system will be transported to BNL and reinstalled in PHENIX.

ORNL DWG 97-3402

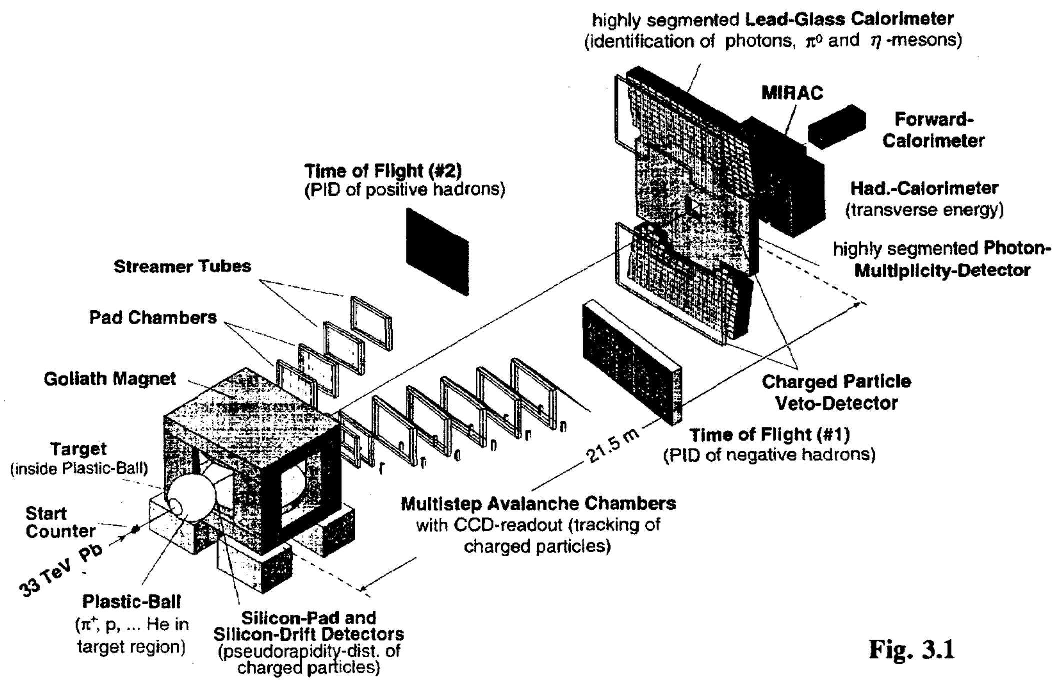

Fig. 3.1

THERMAL DIRECT PHOTON PRODUCTION IN HIGH-ENERGY S+Au COLLISIONS

WA80 Collaboration
BNL, GSI Darmstadt, Kurchatov Inst. Moscow, LBL, U. of Lund, U. of Muenster, ORNL, U. of Tennessee

ORNL Collaborators: T. C. Awes, F. E. Obenshain, F. Plasil, S. Saini, S. P. Sorensen, P. W. Stankus, G. R. Young

The goal of high-energy nucleus-nucleus collisions is to investigate the properties of nonperturbative, finite-temperature QCD; that is, a highly excited (i.e., $T > m_\pi$), many-body, localized system of quarks and gluons. Assuming the system is thermalized, what temperatures does it reach? and what is its heat capacity ε/T^4 as a function of temperature? are two of the more important questions. A long-standing prediction of lattice QCD has been that the heat capacity of a quark-gluon system will experience a sharp rise above some critical temperature of ~180 MeV, as shown in Fig. 3.2; this rise is usually interpreted as the opening of quark degrees of freedom at a deconfining phase transition.

A whole range of experiments have been carried out using beams of O, Si, and Au at 11–15 GeV/nucleon at the BNL-AGS and beams of O, S, and Pb at 160–200 GeV/nucleon at the CERN-SPS as part of this investigation. But the majority of these experiments measure the production of secondary hadrons, which interact strongly and hence will carry only information about the later, presumably cooler stages of the collision. Electromagnetic probes such as photons and dilepton pairs, however, will survive unaffected from the earliest stages of the collision and could, therefore, provide information about hot QCD directly.

In the WA80 experiment at CERN, photon and neutral meson production was measured in collisions of S+S and S+Au at 200 GeV/nucleon using a large (~3800 element) segmented lead-glass calorimeter system. Determining what segment of the observed photons comes from direct, prompt production vs that which results from hadron decays (typically 90+%) is a difficult analysis. From a detailed examination of WA80 S+Au data, it was concluded that no direct photon production was visible at the level of 5% of the inclusive production, for any photon transverse momentum in the range from 0.5 to 2.5 GeV/c. This measurement[1] remains the world's best for direct photon production in high-energy heavy-ion collisions.

The rate of direct-photon production at high transverse momentum from a thermally radiating system will vary as $\sim exp(-P_t/T)$, and will, therefore, be very sensitive to the system's temperature for $P_t >> T$. Accordingly, the limit set by WA80 in the high-P_t range allows us, in turn, to set an upper limit on the possible temperature of a thermalized early stage of the S+Au collision. We can also obtain an estimate of the energy density of the S+Au system as measured through global calorimetry in WA80,[2] and thereby establish a lower limit for the system's heat capacity, ε/T^4. These two limits are indicated on the graph in Fig. 3.2. They define, in effect, a region in which the parameters describing the initial state of the high-energy S+Au collision must lie, in rough agreement with the prediction of lattice calculations.

ORNL DWG 97-3403

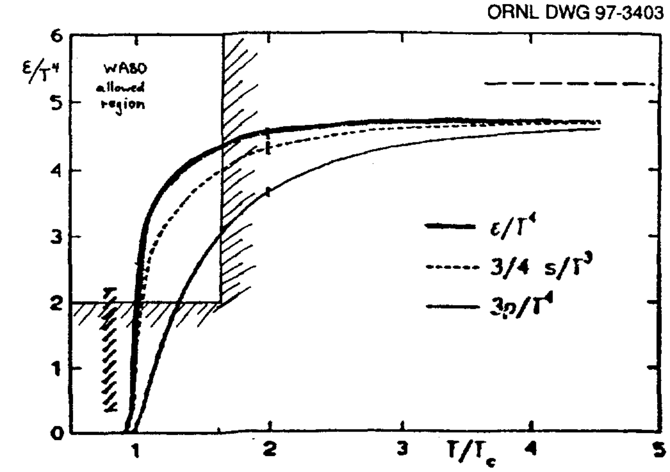

Fig. 3.2

1. R. Albrecht et al., *Phys. Rev. Lett.* **76**, 3506 (1996).
2. R. Albrecht et al., *Phys. Rev. C* **44**, 2736 (1991).

STATUS OF THE WA98 CALORIMETER ANALYSIS

WA98 Collaboration
(For a complete list of authors, see article "CERN WA98 Experiment.")

The group has continued to be responsible for the operation of the WA98 Midrapidity Calorimeter (MIRAC) and for the analysis of the resulting data. This device is one of the principal event-characterizing devices for the WA98 experiment, and it has been a rich source of physics results in and of itself.

During the heavy-ion runs of 1994-1996, MIRAC was used to study the transverse energy produced in collisions at 158 GeV/nucleon of ^{208}Pb ions with targets of ^{58}Ni, ^{93}Nb, and ^{208}Pb. The calorimeter, which has an acceptance of $3.5 < \eta < 5.5$, was also used to study proton-induced collisions in the spring of 1996. The distributions, $d\sigma/dE_T$ and $dE_T/d\eta$, and discussions of the systematic variation of transverse energy production as a function of the number of wounded nucleons have been presented at several conferences, including the APS-DNP Meeting in Cambridge, MA, in October 1996 and at Quark Matter '96, held in Heidelberg, Germany, in May 1996.

Some of the qualitative features of the $d\sigma/dE_T$ distributions, shown in Fig. 3.3, illuminate the physics of these collisions. Even though Pb+Ni and Pb+Nb are asymmetric systems, the shape of the $d\sigma/dE_T$ distributions for these targets is similar to that of Pb+Pb. In the case of large projectile and small target nuclei, as well as in symmetric collisions, one continues to wound more nucleons in the projectile with increasing collision centrality. This results in cross sections for all three systems which decrease monotonically as a function of E_T.

In earlier work, it was observed that the peak of the transverse energy distribution, $dE_T/d\eta|_{max}$, scaled linearly with the number of participants in the collision. This number of participants is proportional to the volume of overlap of the two nuclei during the collision. Figure 3.3 shows $dE_T/d\eta|_{max}$ results plotted against the average number of wounded nucleons for a number of centrality cuts. The new data are consistent with a continuing linear relationship between the number of wounded nucleons and the peak value of E_T production. Although the interpretation of this interesting trend is not finalized, at first glance, there seems to be no evidence for a saturation in the amount of transverse energy produced per struck nucleon, even in collisions of the heaviest available nuclei. Prior to the availability of these data, expectations for these collisions had ranged from one extreme (increased nuclear transparency) to the other extreme (enhanced nuclear stopping), both of which would have strongly affected the trend shown here.

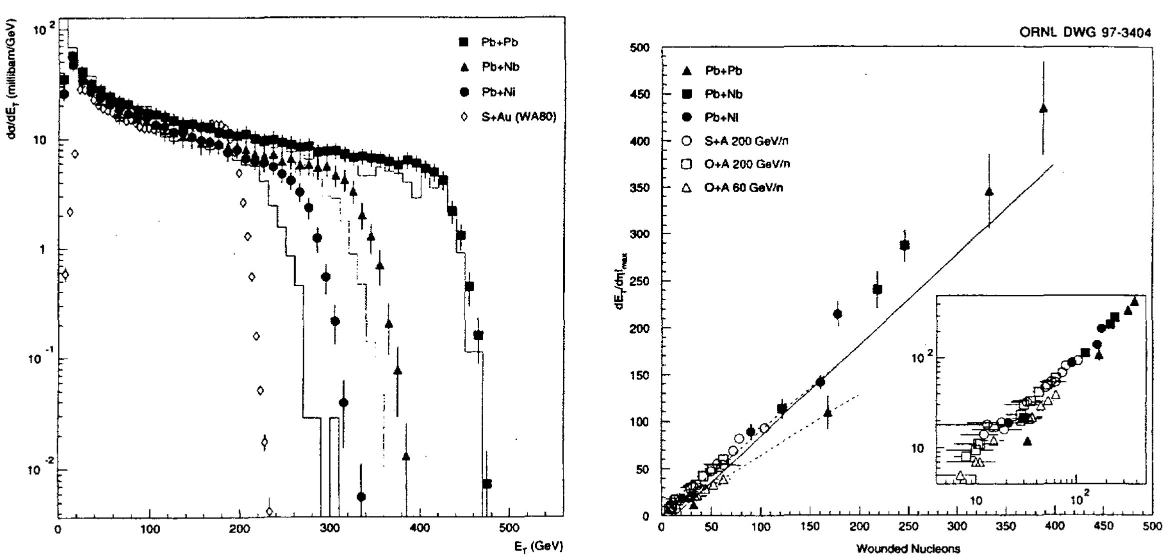

Fig. 3.3. The figure on the left shows the experimental $d\sigma/dE_T$ distributions for 158-GeV/nucleon Pb+Ni, Pb+Nb, and Pb+Pb. The figure on the right shows the linear relationship between the peak value of E_T production and the number of nucleons wounded in the collision.

SOFT PHOTON PRODUCTION IN CENTRAL 200-GeV/NUCLEON ^{32}S+Au COLLISIONS

WA93 Collaboration
U. of Geneva, GSI Darmstadt, INS Warsaw, *U. of Jammu, Kurchatov Inst., KVI Groningen, U. of Lund, U. of Muenster, ORNL, U. of Panjab, U. of Rajasthan, U. of Tennessee, U. of Utrecht, VECC Calcutta*

ORNL Collaborators: T. C. Awes, F. E. Obenshain, F. Plasil, S. Saini, S. P. Sorensen, G. R. Young

The production of photons in ultrarelativistic heavy-ion collisions is of special interest because electromagnetic radiation from the hot system created in such reactions is a probe undisturbed by hadronic interactions. Such *direct* photons may yield information from the early dense phase of the reaction. Direct photon measurements can provide constraints on the initial temperature reached in these collisions. Data on direct photons in 200-GeV/nucleon ^{32}S+Au collisions have recently been published by the WA80 Collaboration.[1] In the WA80 experiment photons have been measured with a lead-glass calorimeter, which has natural limitations for the measurement of low-energy photons. Therefore, a small detector using BGO scintillating crystals was developed for the WA93 experiment. It consisted of an 8×8 matrix of 64 crystals each with a cross section of 25×25 mm^2 and a length of 250 mm (22 radiation lengths). Details about the detector can be found in Ref. 2.

Figure 3.4 shows the cross section of inclusive photons for central reactions of 200 *A* GeV S+Au as a function of the transverse momentum. The data show the expected fall-off, which is only approximately exponential in this representation. Data from WA80 are included for comparison.[1] In the region of overlap the two data sets are in good agreement with each other. However, this measurement enlarges the p_T range of the photon measurement down to very low values with a high accuracy.

One can compare the measured low-p_T cross section of inclusive photons with that expected from hadron decays. For this purpose we have taken π^0 spectra measured by WA80 (Ref. 3) and calculated the decay photons from π^0, η, η', and ω, where an appropriate m_T scaling was applied for the heavier mesons.[1] Below p_T = 0.4 GeV/c the π^0 spectrum has been extrapolated with an exponential in m_T of inverse slope parameter T = 210 MeV. The decay photon spectrum has been normalized to the measured distribution for p_T = 0.5 GeV/c. The result is included in Fig. 3.4 as a solid histogram (simulation 1). While the shape of the inclusive photon spectrum is well described by the decay photons for p_T > 0.5 GeV/c, the measured photon yield deviates from this prediction for lower transverse momenta — the measured yield is significantly larger.

We have tried a modified function which includes a second exponential in m_T. This function fits the experimental π^0 spectra very well with an additional slope of T_2 = 100 MeV.[3] The additional component represents almost 50% of the total integrated yield in the spectrum. The result of the simulation using this function is displayed as a dashed histogram (simulation 2) in Fig. 3.4. This simulation describes the data much better, but still the measured photons for $p_T \leq$ 68 MeV/c exceed the simulation by almost a factor of three. Additional mechanisms, e.g., the γ-decay modes of resonances which may contribute at low p_T (Δ, Σ), have to be investigated.

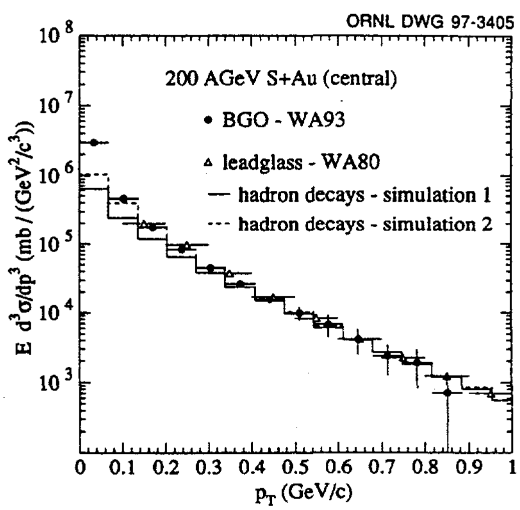

Fig. 3.4

1. R. Albrecht et al., *Phys. Rev. Lett.* **76**, 3506 (1996).
2. K.-H. Kampert et al., *Nucl. Instrum. Methods Phys. Res. A* **349**, 81 (1994).
3. D. Stueken, Ph.D. Thesis, University of Muenster, Germany, 1996, in preparation.

AZIMUTHAL ANISOTROPY OF PHOTONS IN S + Au REACTIONS AT 200 A GeV

WA93 Collaboration
(For a complete list of authors, see article "Soft Photon Production . . .")

Azimuthal correlations of photons produced at midrapidity in 200 A GeV S + Au collisions have been studied using a preshower photon multiplicity detector (PMD) in the WA93 experiment. The transverse flow is studied via the anisotropy of the event as a function of centrality using the second-order Fourier coefficient of the azimuthal particle distribution within one event[1]:

$$\mathbf{Q} = \sum_{\nu=1}^{M} \omega_\nu e^{2i\phi_\nu} \equiv [Q\cos(2\Phi), Q\sin(2\Phi)],$$

where ϕ_ν is the azimuthal angle of particle ν and ω_ν is a weight factor. Only the spatial distribution of particles is studied by taking $\omega_\nu = 1$. After subtraction of the detector effects, the event anisotropy α, is obtained as $\alpha = |\mathbf{Q}|/M$. The event anisotropy extracted in this way will contain an anisotropy due to correlated particle emission or collective effects, $\bar{\alpha}$, and a contribution due to the finite multiplicity.

The event plane correlation technique has been used to determine the true event anisotropy. The particles of each event are distributed into two arbitrary, equal-sized groups (subevents). For both subevents, the Fourier coefficients $\mathbf{Q}^1$ and $\mathbf{Q}^2$ are constructed and the orientations of the event planes (Φ_1, Φ_2) are determined. The angle between the two event planes, $\Psi = \Phi_1 - \Phi_2$, is calculated. In the case of finite multiplicity effects alone, there will be no correlation between the two event planes, and Ψ will have no preferred value. If, however, collective effects are present, a correlation between the event planes will exist and will result in an enhancement of the Ψ distribution at small values of Ψ. The distributions of relative angles Ψ between the event planes for the two subevents are shown in Fig. 3.5 for four centrality bins for the experimental, simulated (VENUS) and mixed-event data sets. The normalized probability distribution of Ψ can be shown to have the form[1]:

$$\left(\frac{dP}{d\Psi}\right)_{\text{normalized}} = 1 + \bar{\alpha}^2 M \frac{\pi}{2} \cos(2\Psi),$$

where the true event anisotropy $\bar{\alpha}$ sets the overall strength of the observed correlation. The resulting true anisotropies $\bar{\alpha}$ from the present analysis are plotted in Fig. 3.6. The observed anisotropy decreases with decreasing impact parameter, as expected for collective flow, suggesting that collective flow of the participant matter is present at SPS energies. The VENUS event generator with rescattering and proper simulation of the detector response cannot explain the observed anisotropy.

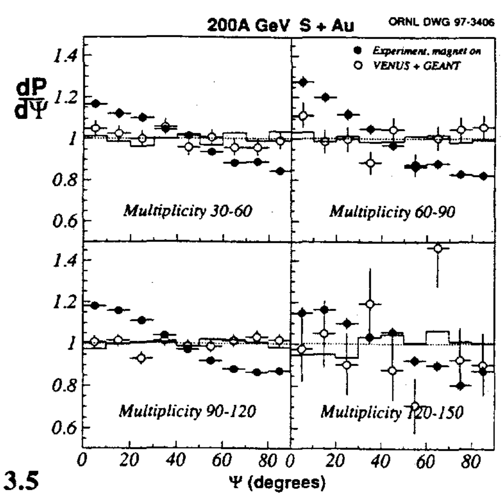

Fig. 3.5

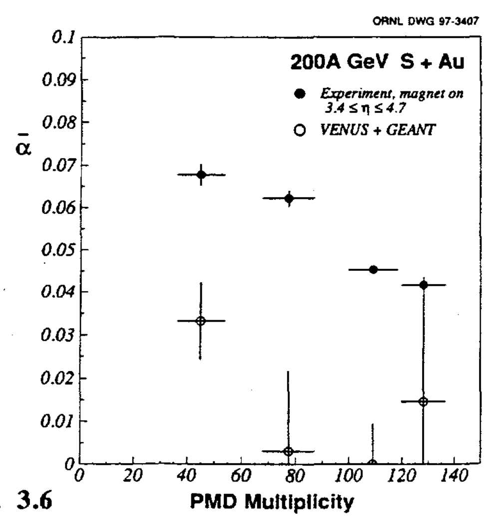

Fig. 3.6

1. J. -Y. Ollitrault, *Nucl. Phys. A* **525**, 561c (1995).

EVENT-BY-EVENT MEASUREMENT OF < p_T > OF PHOTONS IN S+Au COLLISIONS AT 200 A GeV

WA93 Collaboration

(For a complete list of ORNL authors, see article "Soft Photon Production . . .")

It has been suggested that the study of the variation of the mean transverse momentum $<p_T>$ of the produced particles with the global multiplicity could provide a signature for the phase transition from hadronic matter to quark gluon plasma. For a thermalized system at rest undergoing a phase transition, $<p_T>$ is expected to vary with multiplicity like the temperature with the entropy density. It is expected to increase below the transition, then saturate in the transition region and then increase again above the transition. Several experiments have measured the inclusive p_T-spectra of produced particles and have derived $<p_T>$ as a function of rapidity density. It has been reported that $<p_T>$ of charged particles increases with increasing rapidity density and saturates at the highest rapidity densities.[1,2] The WA80 Collaboration has reported a similar behavior for photons and π^0's (Ref. 3) in ^{16}O-induced reactions. For photons, $p_T = E_T^{em}$, the transverse energy of the electromagnetic particles. Thus, if, for a given event, the transverse electromagnetic energy E_T^{em} and the number of contributing photons, N_γ, are measured in the same acceptance, then the ratio E_T^{em}/N_γ gives a measure of the $<p_T>$ of the photons in the event. If N_γ is large (of the order of a few hundred), the result becomes statistically significant on an event-by-event basis.

In the WA93 experiment at the CERN SPS, E_T^{em} and N_γ were measured using the Midrapidity Calorimeter (MIRAC) and the Photon Multiplicity Detector (PMD), respectively. The PMD is a fine-granularity preshower detector; and details of its design, along with methods for extracting photon hit positions, efficiencies, and backgrounds, have been described in Ref. 4. The PMD and MIRAC have a good overlap in pseudorapidity, the region of overlap with complete azimuthal coverage being $3.3 \leq \eta \geq 4.8$. The centrality dependence of the ratio E_T^{em}/N_γ has been studied using E_{ZDC}, the energy deposited in the Zero Degree Calorimeter. Figure 3.7 shows the centrality dependence of $<E_T^{em}/N_\gamma>$ as a function of E_{ZDC}/E_{beam}. The brackets on the top and bottom of the data points indicate the limits due to the systematic error. Unlike the observation of the WA80 experiment for ^{16}O-induced reactions,[3] where the truncated $<p_T>$ varied from 215 MeV/c for central events to 190 MeV/c for the peripheral events, there is no marked centrality dependence observed in the present case. All of the values lie within a band around 170 MeV/c. This difference may arise due to the different low p_T cutoffs in the two cases. While the p_T acceptance in the present case extends to well below 30 MeV/c, there was a large cutoff of 400 MeV/c in the ^{16}O data.[3] The results are consistent with the predictions of the VENUS event generator.

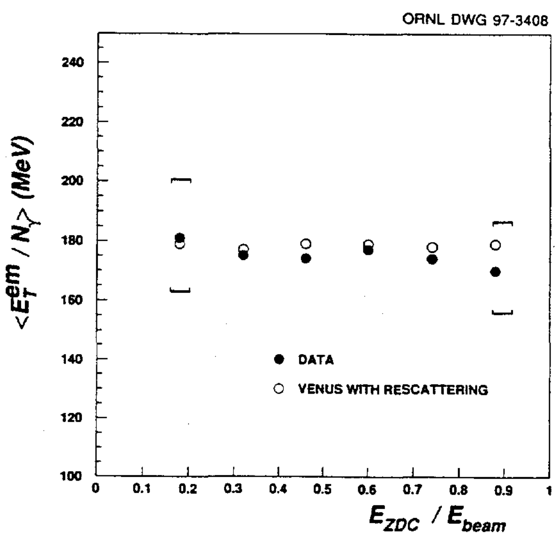

Fig. 3.7

1. G. Arnison et al., UA1 Collaboration, *Phys. Lett. B* **118**, 167 (1982).

2. T. Akesson et al., HELIOS Collaboration, *Z. Phys. C* **46**, 361 (1990).

3. R. Albrecht et al., WA80 Collaboration, *Phys. Lett. B* **201**, 390 (1988).

4. M. M. Aggarwal et al., *Nucl. Instrum. Methods Phys. Res. A* **372**, 143 (1996).

MULTIPLICITY AND PSEUDORAPIDITY DISTRIBUTION OF PHOTONS IN S+Au REACTIONS AT 200 A GeV

WA93 Collaboration

(For a list of ORNL authors, see article "Soft Photon Production . . .")

A preshower detector has been used to measure the multiplicity and pseudorapidity distributions of photons in S + Au collisions at 200 A GeV. The photon multiplicity detector (PMD) of the WA93 experiment is the first implementation of its kind. The PMD consisted of 7500 plastic scintillator pads of $20 \times 20 \times 3$ mm^3 placed behind a $3X_0$ lead converter plate.[1]

The minimum-bias distribution of the photon multiplicity, N_γ, for the pseudorapidity region $3.3 \leq \eta \leq 4.8$ is shown in Fig. 3.8. The horizontal bars represent the systematic error in the determination of N_γ. The shape of the distribution is essentially determined by the collision geometry. The tail region has a Gaussian shape, as shown by the dashed line fit, resulting from fluctuations in the number of participants when the nuclear overlap is complete. The prediction of the VENUS event generator (Ref. 2) with rescattering is superimposed on Fig. 3.8 for comparison.

Gaussian fits have been made to the photon pseudorapidity density distributions to extract the shape parameters, i.e., the maximum value ρ_{max}, the peak position η_{peak}, and the width σ for different centrality bins. The results are shown in Fig. 3.9 as a function of E_T. The results are again compared to the VENUS event generator. The width and centroid of the pseudorapidity distribution of photons vary little with centrality in good agreement with VENUS, while the measured ρ_{max} values increase somewhat faster than predicted. It is instructive to compare the photon multiplicity results with the charged-particle multiplicity results measured for the same system in the WA80 experiment.[3] Instead of a constant width of 1.4 observed for the photon measurement, the width of the charged-particle distribution decreases from about 1.9 to about 1.5 with increasing centrality. This difference may be attributed to the increasing degree of stopping of the participant nucleons.

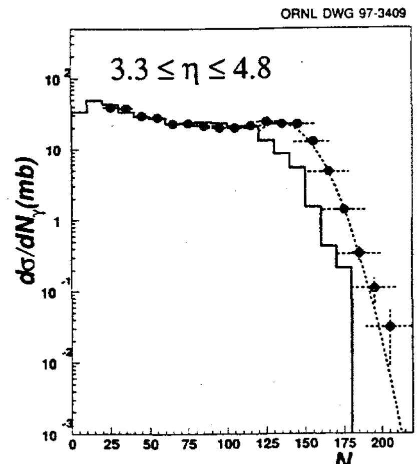

Fig. 3.8. Minimum-bias distribution of photon multiplicity, N_γ. The horizontal bars indicate the extent of the systematic errors on N_γ. The solid line represents the VENUS results for comparison. The dashed line shows a Gaussian fit to the tail region.

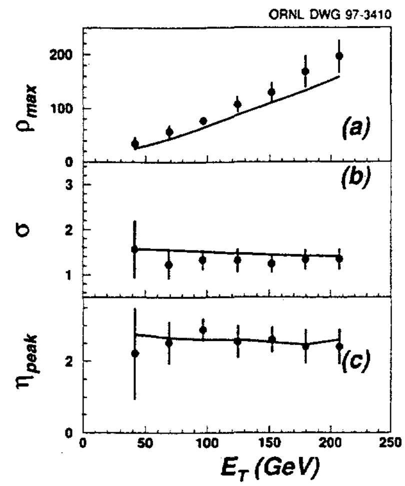

Fig. 3.9. Variation of the shape parameters describing the pseudorapidity distribution of photons for S+Au collisions for different centralities (defined by E_T). VENUS results for similar centrality classes are superposed for comparison, as shown by the solid line.

1. M. M. Aggarwal et al., *Nucl. Instrum. Methods Phys. Res. A* **372**, 143 (1996).

2. K. Werner, *Phys. Rev. Lett.* **62**, 2460 (1989).

3. R. Albrecht et al., *Z. Phys. C* **55**, 539 (1992).

MEASURING DIRECT PHOTON PRODUCTION IN HIGH-ENERGY Pb+Pb COLLISIONS

WA98 Collaboration
(For a list of ORNL authors, see article "CERN WA98 Experiment.")

The CERN experiment WA98 is a wide-ranging investigation of Pb-induced reactions in the relativistic regime 160 A GeV/c. One of the major components of that investigation is study of the production of direct photons. Direct photons, along with virtual photons detected as lepton pairs, are an important probe of the high-energy heavy-ion collision environment because, once produced, they emerge from the nuclear system with very little re-interaction. Thus, they can provide direct information about the early stages of the collision that can only be inferred indirectly via the measurement of hadron production.

There are three possible main sources of final-state photons in a high-energy heavy-ion collision: (1) thermal radiation from a quark-gluon plasma or other hot nuclear matter; (2) hard QCD processes, i.e., parton-parton collisions; and (3) decay products of neutral mesons, particularly π^0's and η^0's. While the thermal-source production has the most direct bearing on the physics of high-temperature nuclear matter, the QCD production bears on gluon structure functions which have never been measured in nucleus-nucleus collisions. The measurement of neutral mesons complements WA98's charged-meson production results.

WA98 measures photon production in Pb+Pb collisions using a large, laterally-segmented lead-glass calorimeter array of over 10,000 elements. (See figure on page 3-3.) Photons deposit their energy via their electromagnetic showers spread over several modules, allowing photon positions to be reconstructed to within a few millimeters and their energies to within a few percent. (This is true even for overlapping showers.) The first step in obtaining direct-photon results is the extraction of neutral-meson production, since their decay photons account for the large majority of all observed photons. Mesons are reconstructed by calculating the invariant masses of all photon pairs within each event. The inset of Fig. 3.10 shows the spectrum of pair invariant masses observed for a small transverse momentum range. It consists of the π^0 peak obscured by a large and broad combinatorial background. The main graph shows the pion peak clearly after the background has been subtracted by means of the mixed-events technique. This technique has been shown to be successful for peak/background ratios of less than 1%.

Once the meson spectra are known, the photons originating from their decays can, in principle, be subtracted from the inclusive photons, yielding the direct photons. This analysis has not been completed. It is anticipated that the extensive WA98 data set (about 40 million events) will allow the extraction of direct photon results at p_T values as high as 4-5 GeV/c. This should provide sensitivity to thermal sources with temperatures in the 200- to 300-MeV range, and to partonic production in the x_T > 0.4 range.

ORNL DWG 97-3417

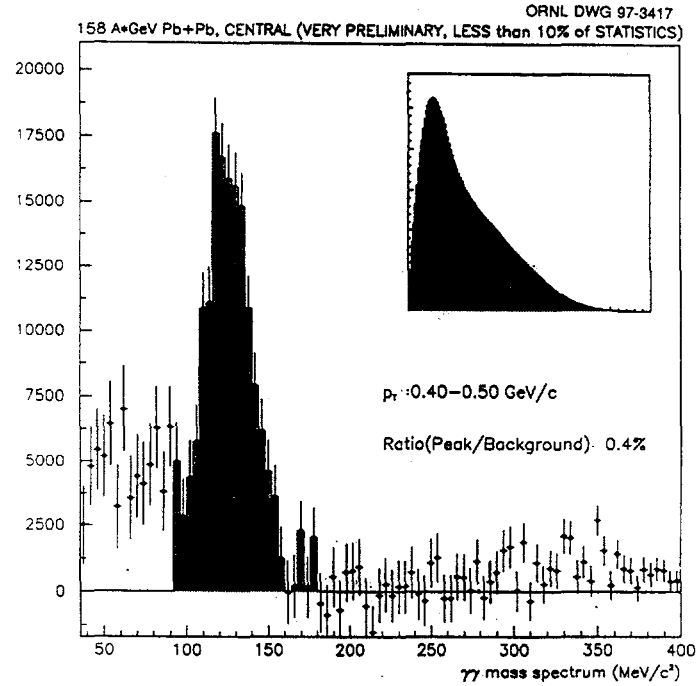

Fig. 3.10

SEARCH FOR DISORIENTED CHIRAL CONDENSATES IN 158 A GeV Pb+Pb COLLISIONS

WA98 Collaboration

(For a list of ORNL authors, see article "CERN WA98 Experiment.")

Disoriented chiral condensates may form in large hot regions of hadronic matter where the approximate chiral symmetry of QCD has been briefly restored. The decay of this region induces a nonequilibrium relaxation of the chiral fields which is predicted to create coherent sources of soft pion modes.[1] The charge of the pions emitted from the DCC has a characteristic probability distribution[2,3]: $P(f) = 1 / (2\sqrt{f})$, where $f = (N_{\pi^0}) / (N_{\pi^0} + N_{\pi^+} + N_{\pi^-})$.

The MiniMax experiment has performed the only systematic search for DCCs in $p\bar{p}$ collisions at the Tevatron, reporting particle production consistent with a binomial partition of neutral and charged particles.[4] Until now there have been no studies using the simultaneous measurement of charged and neutral multiplicities in heavy-ion collisions at any energy.

We have used the WA98 apparatus to search for the production of disoriented chiral condensates in 158 A GeV Pb+Pb collisions. By comparing the correlation of the charged and neutral multiplicities, measured on an event-by-event basis as shown in Fig. 3.11, to a model mixing a DCC signal into VENUS 4.12 events, we have set a 90% CL upper limit on the frequency of DCC production as a function of its size, as shown in Fig. 3.12.

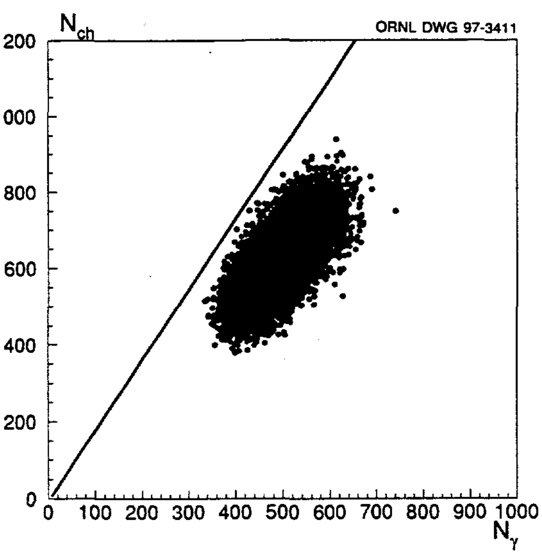

Fig. 3.11. Scatter plot showing correlation of N_{ch} and N_γ on an event-by-event basis.

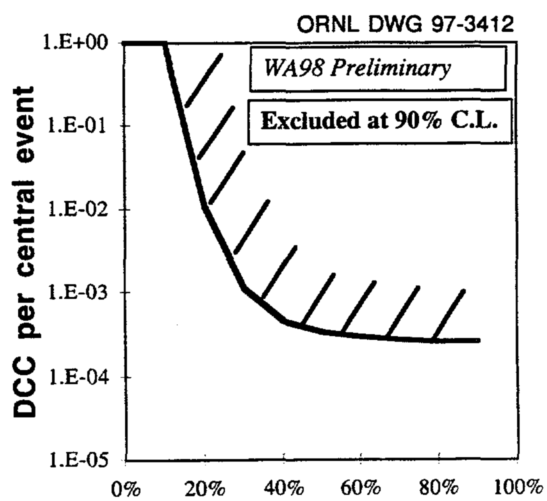

Fig. 3.12. Upper limit of DCC production frequency as a function of DCC size. The line indicates the 90% C.L.

In the near future, we plan to increase our statistics of analyzed data by about two orders of magnitude, which will lower our upper limit if no candidates appear. We are also planning to perform similar analyses in narrower regions of phase space and consider correlations of multiplicity fluctuations within individual events.

1. K. Rajagopal in Quark-Gluon Plasma 2, ed. R. Hwa, World Scientific, Singapore (1995) and references therein.

2. J. D. Bjorken, K. L. Kowalski, and C. C. Taylor, SLAC-PUB-6109, April 1993; J. D. Bjorken, SLAC-PUB-6488, April 1994.

3. A. Anselm and M. Ryskin, *Phys. Lett. B* **226**, 482 (1991).

4. MiniMax Collaboration, submitted to *Physical Review D*, hep-ph/9609375.

PHENIX EXPERIMENT AT RHIC

ORNL and University of Tennessee members of the PHENIX Collaboration include
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The PHENIX experiment emphasizes detection of lepton pairs, photons, and identified hadrons over a wide range in p_T and mass. PHENIX will have good counting statistics out to $p_T/M > 2$, i.e., over the region where QGP is best distinguished from hadron gas. PHENIX is as inclusive as possible regarding various potential signatures of QGP formation and looks for correlated changes in several observables as a function of charged-particle rapidity density. PHENIX emphasizes fine granularity and includes several specialized detectors to handle electron, muon, and photon detection. An isometric view of the detector is shown in Fig. 3.13.

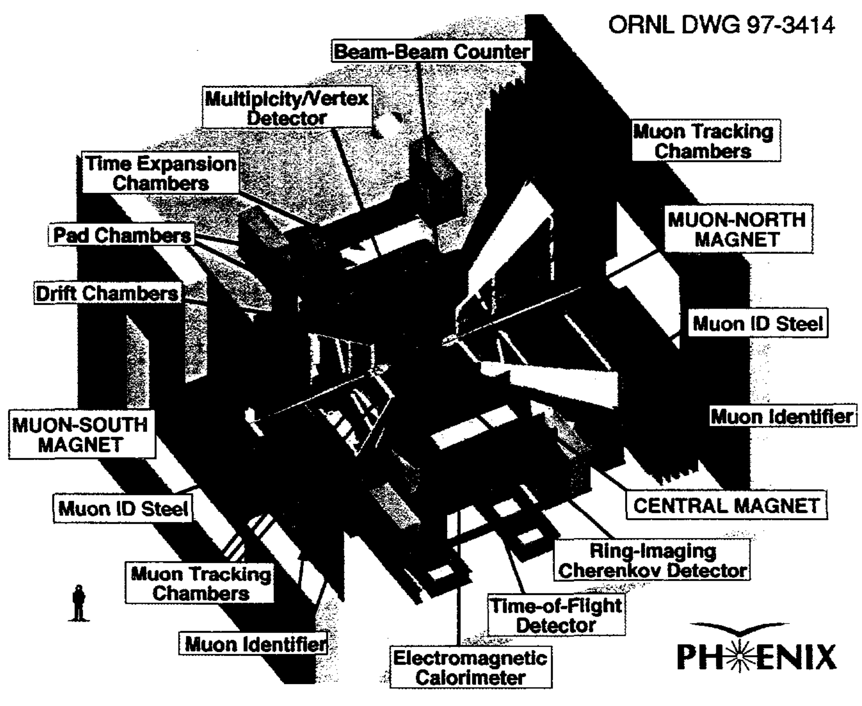

Fig. 3.13. Isometric view of the PHENIX detector, showing the various spectrometer elements.

ORNL concentrates on the physics to be performed with the muon arms and the EM calorimeter, and works on the construction of the muon identifier and on the installation in PHENIX of the WA98 lead-glass detector. Funding for one of the muon arms is provided under DOE's RHIC Additional Experimental Equipment (AEE) program. The second muon arm is funded from Japanese funds as part of an initiative to use polarized proton beams at RHIC to study spin physics.

1. University of Tennessee, Knoxville.
2. ORNL Instrumentation and Controls Division.
3. Adjunct research participant from University of Tennessee, Knoxville.

THE PHENIX MUON ARMS

PHENIX Collaboration
(For a list of ORNL authors, see article "PHENIX Experiment at RHIC.")

The purpose of the PHENIX Muon Arms subsystem is to enable the study of vector mesons decaying into dimuons, to allow the study of the Drell-Yan process, and to provide the muon detection in $D\bar{D} \rightarrow \mu + e + X$ as part of both the relativistic heavy-ion and the spin physics programs of PHENIX. Each muon arm must both track and identify muons, as well as provide good rejection of pions and kaon. Therefore, both a Muon Tracker and a Muon Identifier are needed.

Each of the two arms of the Muon Tracker comprises three stations of tracking chambers, with three planes of cathode strip chambers (CSC) each, mounted inside the end-cap muon magnet. Two different construction techniques are used for the chambers. The first and third stations are constructed as honeycomb panels with cathode strips on the inside surfaces. The second (central) stations are constructed as stacks of wires and etched foils attached to aluminum frames. The position resolution will be 100 μm per plane which provides a mass resolution sufficient to separate the J/ψ from the ψ' and the $\Upsilon(1S)$ from the $\Upsilon(2S{+}3S)$.

Full-scale prototypes of the muon tracker station 1 honeycomb lattice CSC and of the station 2 etched foil CSC have been constructed and tested. A prototype of the charge-sensitive preamplifier for the CSC readout is being manufactured.

The north and south muon identifiers are located behind the 30-cm muon-magnet endplate. Each consist of 6 gaps instrumented with plastic proportional tubes interleaved with 5 layers of steel. Four large and two small aluminum panels are used to tile each gap with tubes. The largest-size panels are approximately 4 m x 6 m x 10 cm. A full-scale prototype of a large muon identifier panel is under construction and will be tested soon. Mass fabrication of certain parts of the muon subsystem will begin in 1997. Details concerning the Muon Identifier subsystem are discussed in the next article in this *Progress Report*.

The primary goal of the Relativistic Heavy-Ion Physics program of PHENIX is to detect the quark-gluon plasma (QGP) and to measure its properties with as many different experimental probes as the detector will allow. The Muon Arms are a major contributor to the overall PHENIX physics program. This subsystem will be used to measure the production of vector mesons decaying into dimuons in heavy-ion collisions for masses ranging from that of the ϕ to the Υ. Measurement of the differential suppression of J/ψ, ψ', $\Upsilon(1S)$, and $\Upsilon(2S{+}3S)$ production will provide information concerning "deconfinement," i.e., Debye screening of the QCD potential. The two muon arms provide large acceptance for high-mass pairs at central rapidity.

The Muon Arms also allow studies of the continuum dilepton spectra in a much broader region of rapidity and mass than is accessible with the central electron arms alone. In addition, the e-μ coincidence using electrons detected by the central arm will probe charm production and aid in the understanding of the shape of the continuum dielectron spectrum. This is because unlike-sign e-μ pairs result primarily from $D\bar{D}$, while like-sign pairs are mainly due to the combinatorial background.

Proton-proton collisions with polarized protons at $\sqrt{s}$ from 50 to 500 GeV will result in the determination of the helicity distributions of quarks and antiquarks and of the gluon polarization in the nucleon. This information is obtained by studying the polarized Drell-Yan process, vector boson production, polarized gluon fusion, and polarized gluon Compton scattering. Antiquark structure function measurements rely on analyzing Drell-Yan and vector-boson production data. Gluon polarization measurements rely on analyzing heavy quark, J/ψ, and prompt-photon data. Efforts to understand the contributions of the spin of sea quarks and the polarization of gluons to the total nucleon spin may help explain the lack of agreement between experimental data and the Ellis-Jaffe sum rule.

THE PHENIX MUON IDENTIFIER

PHENIX Collaboration
(For a list of ORNL authors, see article "PHENIX Experiment at RHIC.")

ORNL has lead responsibility for the design and construction of the PHENIX Muon Identifier subsystem. The north and south muon identifiers each consist of 6 gaps instrumented with plastic proportional tubes interleaved with 5 layers of steel. Four large and two small panels are used to tile each gap with tubes. The largest-size panel is approximately 4 m x 6 m x 10 cm and weighs 3000 lbs. ORNL developed both the conceptual and mechanical engineering design of the identifier panels. Also, ORNL designed the panel rail support system and the installation scenario.

The individual proportional tubes are Iarocci limited-streamer tubes operated at reduced voltage in order to maximize their longevity. Iarocci tubes were chosen because they satisfy all of the required detector performance criteria. They have proven reliability and longevity, compactness, low cost, and are readily available from commercial vendors. They have robust wires and seals. Consequently, such tubes can be used to economically tile large areas. The tubes have a resistive graphite coating on the inner surface that serves as the cathode. The anodes are gold-coated Cu-Be 100-μm-diameter wires. The eight anode wires in each tube are ganged together into one readout channel to allow for low-resolution tracking and to provide signals for the first- and second-level muon triggers. The drift-time interval (for arrival of 90% of pulses) in a tube is approximately 100 ns for a 25:75 Ar-isobutane gas mixture. This drift-time interval is cut in half by forming the logical OR of pairs of back-to-back tubes staggered by half a cell. Such a staggered arrangement also enhances the overall detection efficiency.

A full-scale functional prototype of a large muon-identifier panel is under construction at ORNL. The panel frame and lifting table have been constructed. The Iarocci tubes have undergone a variety of quality-assurance tests. A preliminary data acquisition system is operational. A satisfactory gas distribution system has been constructed and tested. The high-voltage distribution system has been designed and tested. The performance of the completed panel will be tested extensively at ORNL using a cosmic ray telescope and radioactive sources. It will also be tested to ensure robustness under mechanical manipulation.

ORNL also has lead responsibility for developing the front-end electronics (FEE) for the readout of the Muon Identifier. There will be diode protection on all inputs, a total power dissipation of less than 200 mW per channel, and fiber optic connections for all signals in or out of the motherboard (serial, timing, control, and data output). There will be one motherboard per muon identifier panel. There will be 128 to 226 channels per motherboard depending on the panel. There will be one heap manager per motherboard. The muon identifier front-end electronics must be able to perform the necessary Level-1 logic to provide the appropriate information and matching for the Level-1 trigger system to construct one-dimensional trigger roads. Effective Level-1 muon trigger algorithms have been designed.

The massive steel absorber layers of the Muon Identifier were installed inside the PHENIX experimental hall at Brookhaven National Laboratory during the summer of 1996. A Preliminary Design Review of the Muon Identifier system took place in November 1996. A Final Design Review is scheduled for March 1997. Mass fabrication will commence as soon as possible after the successful completion of the Final Design Review.

PHENIX ELECTRONICS WORK

M. Allen,[1] T. C. Awes, C. L. Britton,[2] W. Bryan,[2] L. Clonts,[2] Y. Efremenko,[3] N. M. Ericson,[2] M. Emery,[2] S. Frank,[2] J. Halliwell,[2] G. Jackson,[1] U. Jagadish,[2] Y. Kamyshkov,[3] E. Kennedy,[1] C. Moscone,[1] R. Palmer,[1] F. Plasil, K. F. Read M. L. Simpson,[2] M. Smith,[2] R. Smith,[1] P. W. Stankus, J. W. Walker,[2] A. L. Wintenberg,[2] G. R. Young, and BNL, Kyoto U., LANL, Lund U., McGill U., RIKEN, INS Tokyo, U. Waseda

ORNL participates in electronics development for 7 of the 11 PHENIX detector subsystems: Multiplicity Vertex Detector (MVD), tracking Pad Chamber (PC), Ring-Imaging Cherenkov Counter (RICH), Lead Scintillator Calorimeter (PbSc), Lead-Glass Detector Array (PbGl), Muon Tracker (MuTR), and Muon Identifier (MuID). Work during the period covered by this *Progress Report* is summarized below.

The MVD effort includes design of two integrated circuit (IC) chips, all control logic for the chips and boards, and a set of three types of interface boards. The first IC is a 32-channel chip which includes a charge-sensitive integrator, a discriminator, trigger-sum summing circuitry, and a maskable, settable calibration pulser. The second IC is a combined analog memory unit (AMU) and analog to digital converter (ADC). The control logic has been shown to run at the full 40-MHz clock rate needed. Three interface boards, to handle timing, event data output, and trigger data output, will be designed later this year. Prototypes of all the ICs and heap manager were tested in conjunction with two silicon strip detectors in the spring of 1996 at the AGS.

The PC effort includes development of a 16-channel IC with a charge-sensitive preamplifier and discriminator for each channel and a maskable, settable calibration pulser. Threshold for the discriminator and decay-time constant for the preamp are programmable. Various versions have been built and tested on test chambers exposed to beta sources. One version has been tested in the AGS beam with at full clock rate. It was coupled to a prototype chamber for signal input and a prototype delay memory unit for output. The control-logic and interface board for the PC are being specified and will be developed this coming year.

The RICH, PbSc, and PbGl electronics all require an integrator/discriminator IC, an AMU/ADC IC, and a board set with control logic. The integrator ICs include a charge-integrating preamplifier, variable gain amplifier, fast timing discriminator, TAC, trigger-summing circuitry, a maskable settable calibration pulser, and various programmable set points. Versions of all the integrators, in 4- or 8-channel versions, as appropriate, were built and tested during this period. Work has started on all the control, I/O, and timing functions needed for the boards and will be completed during the coming year.

All individual electronics building blocks for MVD, PC, RICH, PbSc, and PbGl have progressed now through two or more rounds of design, prototype fabrication, and testing. A block diagram of the EMCal (PbSc or PbGl) front-end electronics, which incorporates nearly all the functional block mentioned, is shown in Fig. 3.14.

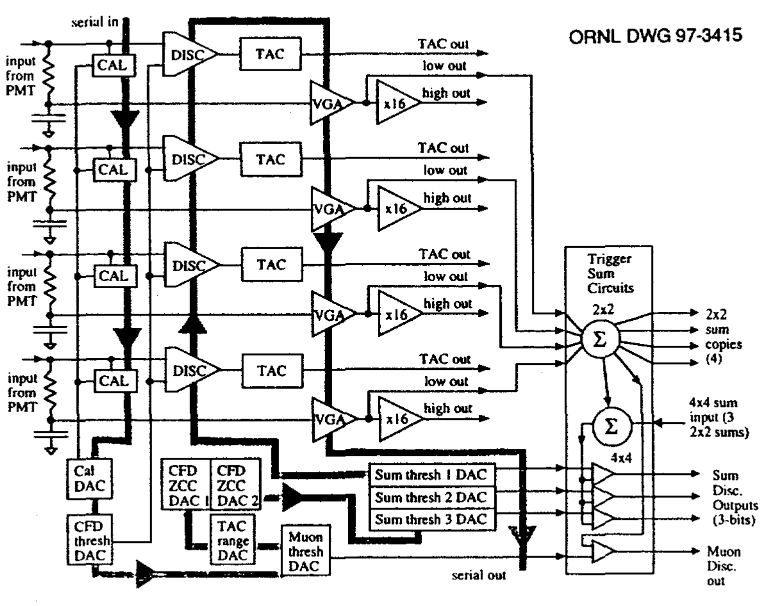

Fig. 3.14

1. ORNL Instrumentation and Controls Division.
2. University of Tennessee, Knoxville.
3. Consultant under subcontract from the University of Tennessee, Knoxville.

PHENIX OFF-LINE COMPUTING SYSTEM

Han Geng,[1] D. P. Morrison,[1] V. Perevoztchikov,[1] S. P. Sorensen,[2]
Yan Zhao,[1] An Dehai,[3] Li Qun,[3] Liu Qihang,[3] Xu Rongsheng[3]

The purpose of the PHENIX off-line computing system is to provide all aspects of data and information handling that are not directly connected to the collection of data and to the monitoring of the experiment. During this reporting period, the work within the off-line group has centered around the design and implementation of a first prototype of the core off-line software: The PHENIX Event Processor (PEP).

PEP has been implemented as a fully-distributed client-server application using the software package PVM (Parallel Virtual Machine) from ORNL/UT as the basis for interprocess communication. As shown in Fig. 3.15, the major components of PEP are:

1. Controller. It oversees the execution of a complete job by keeping track of the states of all active processes and by giving each active process "work assignments."
2. Data Servers. These distribute events from either disks, tapes, or the data acquisition systems for further processing; or they distribute the processed events for storage either on disks or (in the future) in a large-scale hierarchical storage system.
3. Data Operators. These do all the actual "physics" processing of the data, such as calibrations, event reconstruction, detector simulations, etc. These Data Operators will be implemented by the various subgroups within the PHENIX Collaboration.
4. Database Server. This runs remotely on the RHIC computing cluster at BNL, where it accesses the central PHENIX ORACLE database.
5. Data Display. This is currently based on PAW, but we are actively investigating other options.

All data exchanged between processes or modules within a process are handled by the data structure management package (DSPACK) from the University of Birmingham, U.K.

In addition to providing core software for the PHENIX Collaboration, we have also been involved in the planning of the large RHIC Computing Facility (RCF), which is going to provide the bulk of the hardware for the event reconstruction and data analysis of PHENIX data. RCF has recently received approval for its initial funding and will, by 1999, contain more than 100 GFlops of CPU, 20 TBytes of disk storage, and more than 100 TBytes of robotic storage. In addition to this center we are also in the planning phase for an additional facility in Japan, which will complement the RCF by providing simulation capacity for PHENIX, which will not be available at RCF.

ORNL DWG 97-3416

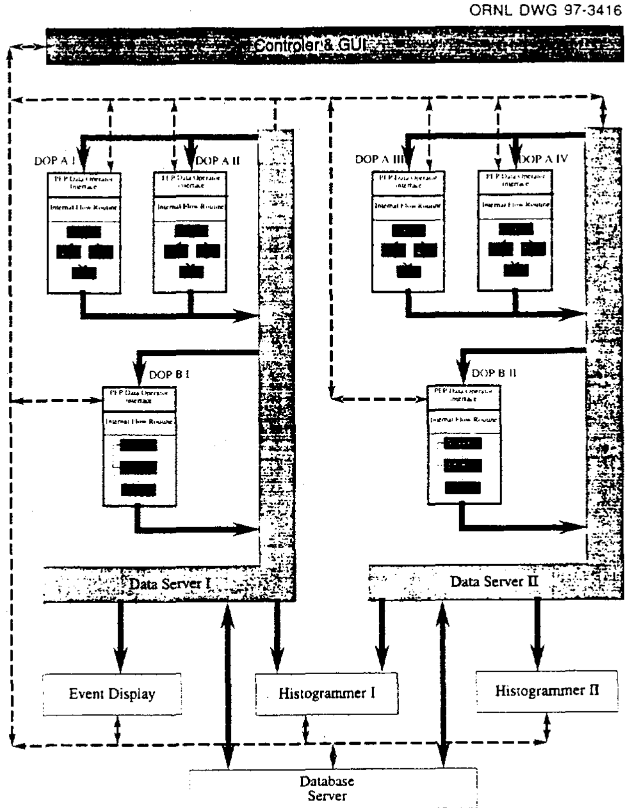

Fig. 3.15. Schematic view of a possible configuration of the PHENIX event processor PEP.

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1. University of Tennessee, Knoxville.
2. Adjunct research participant from the University of Tennessee, Knoxville.
3. Institute of High Energy Physics, Beijing.

THE $\bar{u}$ vs $\bar{d}$ CONTENT OF THE PROTON: NUSEA AT FERMILAB

E866 / NUSEA Collaboration
Abilene Christian U., ANL, FNAL, Georgia State U., Illinois Inst. of Technology, LANL, Louisiana State U., New Mexico State U., ORNL, Texas A&M U., Valparaiso U.

ORNL Collaborators: T. C. Awes, P. W. Stankus, G. R. Young

The internal structure of the proton as seen in high-energy collisions has been described quite successfully in terms of the quark-parton model: external particles scatter off of single, pointlike entities within the proton, and these can be identified as quarks and gluons. Measurements of the phase-space densities of these partons (i.e., parton distribution functions or PDF's) have been performed in deep inelastic scattering experiments for processes such as $\nu + q \rightarrow l + jet$ and $l + q \rightarrow l + jet$ and also in high-energy hadron–hadron collisions for the processes $q + q \rightarrow jet + jet$ and $q + gluon \rightarrow \gamma + jet$. These kinds of experiments, however, typically provide only indirect information about the PDFs of antiquarks in the proton, which are much less well-known than those of the valence quarks.

One aspect that is not well known, for instance, is the comparison between the PDF's of antiquarks of different flavors, particularly between the $\bar{u}$ and $\bar{d}$ in the proton. Naively, one might expect them to be the identical, and the prediction that their integrals are the same is formalized in the well-known Gottfried Sum Rule (GSR). There have been simple expectations that the GSR may be violated in the case of the proton for quite some time; but interest picked up when the NA51 experiment at CERN found that the difference in the integral of the $\bar{u}$ and $\bar{d}$ PDFs was larger than had been expected. The E866 experiment at Fermilab intends to measure the $\bar{u}-\bar{d}$ difference in a differential form and to a high degree of statistical and systematic accuracy, so that the source of the asymmetry can be investigated.

The E866 experiment accesses the antiquark PDFs by observing the Drell-Yan (DY) process $q + \bar{q} \rightarrow \mu^+ \mu^-$ in a fixed-target dimuon spectrometer. The 800-GeV/c proton beam from the Fermilab Tevatron impinges alternately on targets of liquid hydrogen and liquid deuterium, and the $\bar{u}-\bar{d}$ difference is revealed directly by the ratio of the DY cross sections $\sigma(p + d \rightarrow \mu\mu)/\ 2\sigma(p + p \rightarrow \mu\mu)$. Figure 3.16 illustrates the behavior of this observable as a function of the kinematic variable $\sqrt{\tau} = M_{\mu\mu}/\sqrt{S}$. The curves are predictions for the DY ratio according to different sets of proton PDFs now in current use by the theoretical community. The single NA51 result is shown by means of the open rectangle. The other points are the anticipated E866 results based on one particular PDF assumption (CTEQ). This demonstrates the anticipated statistical and systematic accuracy as well as the kinematic coverage of the E866 experiment, which is expected to distinguish between the different sets of theoretical predictions. The experiment is currently running at FNAL and will continue through the end of the 1996–1997 fixed-target period.

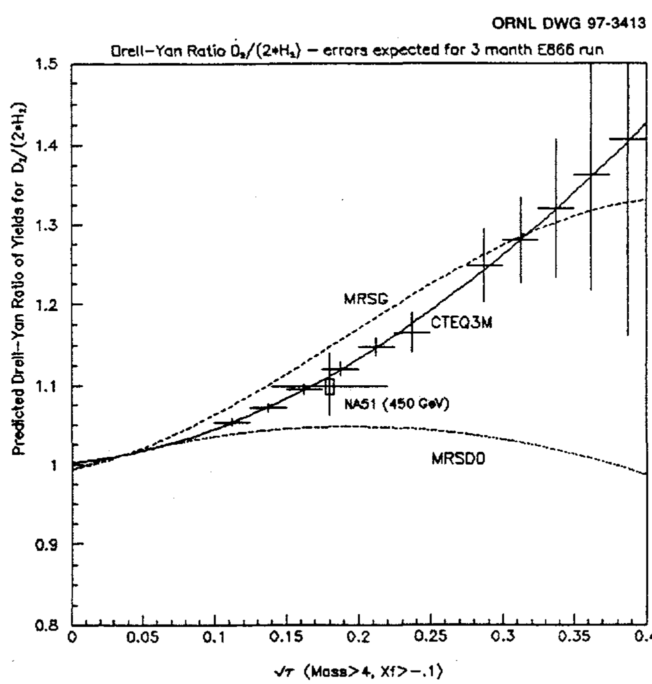

Fig. 3.16

FUNDAMENTAL PHYSICS

DEVELOPMENT OF QUARTZ-FIBER CALORIMETRY

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The goal of this Laboratory-Directed Research and Development project was to study the properties of calorimeters for use in high-energy physics experiments with quartz fibers as the active medium. In such calorimeters the showers initiated by the primary particles are detected via the Cherenkov light produced in the quartz fibers. Following the concepts of forward calorimetry for high luminosity hadron colliders developed within the SSC/GEM Collaboration, we built a prototype of a quartz-fiber calorimeter with zero-degree orientation of fibers relative to the beam direction. The performance of this prototype was studied in the test beam at the Stanford Linear Accelerator (SLAC).

Fibers in the calorimeter prototype are parallel to each other and to the beam direction and are arranged in a rectangular structure inside the brass absorber. The absorber consists of fifty 2-mm-thick and 40-cm-long brass plates stacked on top of each other. Each plate has 50 machined grooves with a cross section of 0.9 x 0.9 mm^2 separated by a distance of 2.3 mm. Each groove contains 3 quartz fibers with diameters 300/330/360 μ (silica core/doped silica clad/polyimide buffer). The sampling fraction (core volume) is 4.6%. There are 22 grooves or 66 fibers per cm^2 of prototype cross section. The fiber length is 70 cm with the first 40 cm located within the absorber. At the back of the module, the fibers are grouped into 6 bundles, each coupled to an XP2012B photomultiplier such that left and right independent readout segments are created and such that the 3 fibers in each groove are connected to 3 different photomultipliers. There is a total of about 6700 fibers in this device.

Using the electron test beam at SLAC, we have measured the response of this prototype to electrons and muons in the energy range 5 to 29 GeV. The energy resolution $\delta E/E = (82.6 \pm 0.4)\%/\sqrt{E}$ was measured. The limit on the constant (energy-indepedent) term in energy resolution of $\leq 3.7\%$ was obtained. The light response of the calorimeter was found to be 2.2 photoelectrons per 1 GeV of incident energy. The calorimeter exhibited excellent linearity in the energy range 5 to 29 GeV.

Possible future applications of this technique include forward calorimeters for experiments at hadron and at heavy-ion colliders, photon Compton polarimeters for polarization measurements of intense electron and positron beams, and other applications where modest energy resolution is acceptable and where high speed, radiation hardness, and insensitivity to low-energy background particles are required.

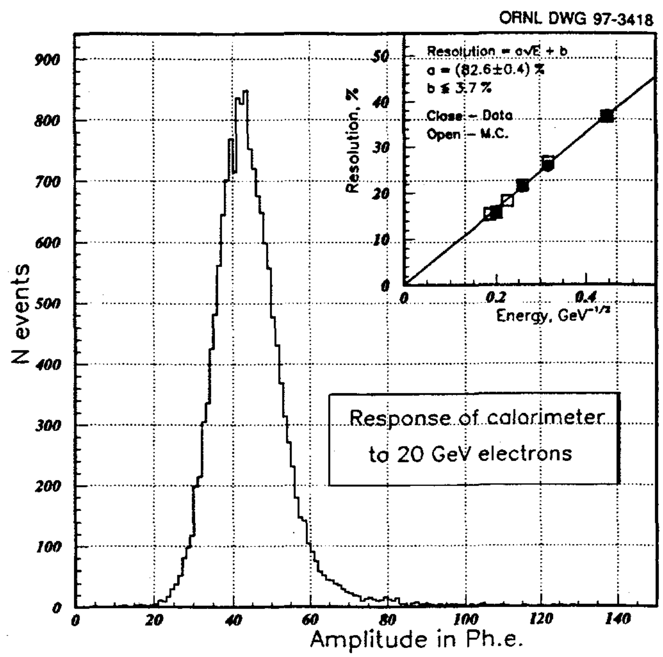

Fig. 3.17. Response (at 20 GeV) and energy resolution vs. energy of quartz-fiber calorimeter prototype.

1. University of Tennessee, Knoxville.
2. Consultant under subcontract from the University of Tennessee, Knoxville.

QUARTZ-FIBER GAMMA POLARIMETER

W. Bugg,[1] S. Berridge,[1] H. Cohn,[1] Y. Efremenko,[2] Y. Kamyshkov,[2] D. Onoprienko,[1] F. Plasil, K. Shmakov,[1] A. Weidemann[1]

We developed, built, and installed a compact quartz-fiber calorimeter (QFC) designed to measure the longitudinal and transverse polarization of the electron beam at the SLD detector at SLAC. The device is complementary to the existing polarimeter, but can, in principle, exceed the measurement capability obtained to date. Longitudinal and transverse polarization of a high-energy electron beam can be measured by detecting the difference in average energy and average angle of photons produced in Compton scattering of electrons off the intense polarized laser beam in different spin states. Our device can provide an independent cross-check of longitudinal polarization and measure the transverse polarization of the electron beam at the SLD.

In order to peform such measurements, both the energy and the position of a narrow gamma beam must be measured to a high degree of accuracy. To measure the transverse polarization, the position must be measured to better than a few microns. For this purpose, the calorimeter must be compact in order to fit into the limited space available; it must be of sufficient thickness to enable the measurement of the total energy; it must be radiation hard to withstand long-term operation without degradation; and it must have adequate segmentation so as to be highly position sensitive. Tungsten absorber and quartz fibers fulfill these requirements. The device consists of thirty-eight 360-μm OD polyimide buffered-quartz fibers which form ribbons that fit tightly into alternating horizontal and vertical slots in tungsten plates. The plates are approximately 5 x 5 cm^2; they are 7 mm thick (two radiation lengths); and they have a density of 18 g/cm^3 (95% W). Thirty-five plates form two independent calorimeters capable of measuring horizontal and vertical positions of the gamma beam. Single-particle resolution is only 1/3 mm. However, for a large number of gammas, it is statistically possible to obtain a spatial resolution of a few microns. The device is positioned very close to the beam pipe without being hit by the very high-intensity synchrotron radiation which is present. The whole assembly is remotely operated with precision motions in both the horizontal and vertical directions.

The fibers exiting the calorimeters are fed to a lead-shielded photomultiplier box which contains 24 PMTs for the horizontal fibers and 24 PMTs for the vertical fibers, in addition to monitoring and calibration devices. High-intensity gallium nitride blue LEDs supply a calibration signal to each PMT via additional quartz fibers. The signal from quartz fibers is Cherenkov light which gives a smaller signal than conventional scintillation detectors, but which allows a large reduction in the background from low-energy synchrotron radiation. Properly shielding all the signal-transport quartz fibers presents a formidable problem. A remotely-activated pneumatic lead shutter was installed to measure extraneous background radiation.

The device operated for the most part according to predictions of Monte Carlo calculations. However, the background was found to be very severe, and it interfered with obtaining the desired and predicted measurement of the polarization. The background is believed to stem from a low-energy halo around the beam, originating from collimators and/or synchrotron radiation. Additional shielding and more careful SLC tuning may be require when polarization measurements are made. At the current level of background, the QFC provided longitudinal polarization measurements with an accuracy of a few percent, consistent with the other SLD polarization measurement made by means of an electron Cherenkov spectrometer.

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1. University of Tennessee, Knoxville.
2. Consultant under subcontract from the University of Tennessee, Knoxville.

STUDY OF QUARTZ-FIBER RADIATION DAMAGE BY GAMMAS AND NEUTRONS

W. Bugg,[1] H. Cohn,[1] Yu. Efremenko,[2] Yu. Kamyshkov,[2] F. Plasil

One of the growing applications of quartz fibers is their use as Cherenkov radiators for measurements of the energy and position of showers produced by high-energy particles in sampling calorimeter detectors. The most attractive features of this technique are the fast detector response and the outstanding radiation longevity of the quartz fibers. Possible applications include forward calorimeters for experiments at hadron and at heavy-ion colliders, photon Compton polarimeters for polarization measurements of intense electron and positron beams, and other applications where low light yield is acceptable and where high speed and radiation hardness are required. In some applications devices exposed to tens of GRads and to neutron fluxes of up to 10^{18} n/cm^2 are required to survive for a few years.

The propagation of Cherenkov light produced in the fiber core along the fibers requires that the fibers be transparent in the wavelength range of 200-600 nm, which corresponds to the sensitivity of conventional photodetectors. Existing experimental data on radiation damage of quartz fibers in the UV range are contradictory and incomplete. Moreover, the mechanism of radiation damage and the practical limitations of quartz fiber applications have not been studied sufficiently.

We performed studies of radiation damage for several different types of quartz fibers produced by industry. Samples included silica quartz fibers with different concentrations of OH^- in the core, doped silica cladding, and various types of buffer coatings (including polyimide and aluminum coatings). Gamma irradiation (up to 23 GRads) was performed using a spent-fuel core element of the HFIR reactor. The irradiation rate was ~70 MRad/hour at the beginning of irradiation, decreasing down to ~15 MRad/hour after 30 days. Neutron irradiation was performed at the ORELA facility. The optical transmission of fibers before and after several irradiation doses was measured in the wavelength range of 200-600 nm by a spectrophotometer.

We have found that for radiation doses of up to 23 GRads, fibers with aluminum buffer and a high OH^- concentration in the core are the most radiation resistant. These fibers preserve their mechanical properties and transparency in the wavelength region of 420-480 nm, corresponding to the maximum sensitivity of the most popular bialkali PMTs. At higher and lower wavelengths, a substantial degradation of the optical transmission of the fibers is observed, which gradually increases with increasing radiation dose.

Studies of self- and temperature-annealing after irradiation were also performed. Self-annealing turns out to be insignificantly small and hardly detectable after 6 months of fiber storage in a non-radioactive environment. On the other hand, temperature-annealing was found to be very efficient. After a few hours of treatment at temperatures above a threshold temperature, all damaged fibers (damaged with either gamma or neutron radiation) were found to have recovered almost to the pre-irradiation transmission level.

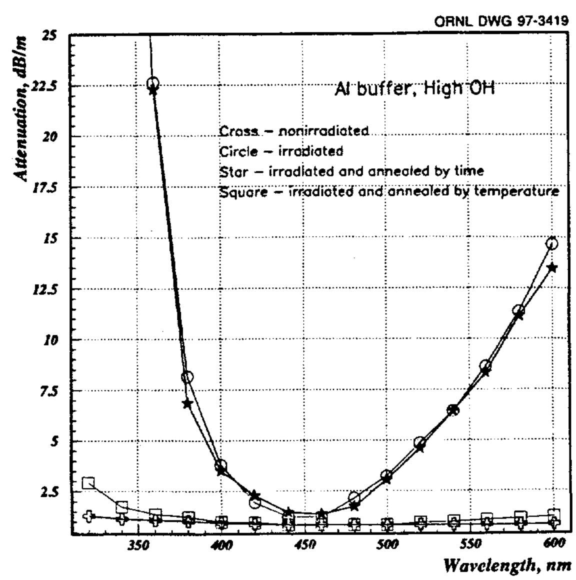

Fig. 3.18. Effects of radiation damage caused by an integral neutron flux of 10^{15} n/cm^2. Self- and temperature-annealing results are also shown.

1. University of Tennessee, Knoxville.
2. Consultant under subcontract from the University of Tennessee, Knoxville.

DESIGN OF AN EXPERIMENT TO SEARCH FOR BARYON NONCONSERVATION IN NEUTRON-ANTINEUTRON TRANSITIONS

W. Bugg,[1] H. Cohn,[1] Yu. Efremenko,[2] Yu. Kamyshkov,[2] R. Lillie,[3] A. T. Lucas,[4] F. Plasil, S. Raman, M. Rennich,[5] D. Selby,[6] K. Shmakov,[1] C. West,[6] G. R. Young

The goal of this Laboratory-Directed Research and Development project was to study the possibility of performing a new experimental search for neutron to antineutron transitions at ORNL's neutron-source facilities. In the contemporary theoretical unification models, the $n \rightarrow \bar{n}$ transition may exist as a complementary or alternative process to nucleon decay. The experimental observation of $n \rightarrow \bar{n}$ transitions would establish a new phenomenon in particle physics, reveal a new domain of energy where "new physics" beyond that reached at the largest accelerators occurs, and provide a major impact on theoretical models of unification of the forces of nature. It could also contribute to the explanation of the "baryon asymmetry" of the universe and provide a precision test of CPT-symmetry through the determination of the mass difference between neutrons and antineutrons. We have designed a HFIR-based experiment which, due to a novel focusing layout, would (for three years of HFIR operation) result in an increase of the $n \rightarrow \bar{n}$ discovery potential by a factor of ~1,000 relative to the most sensitive earlier experiment. Thus, in the HFIR experiment it would be possible to obtain in one day of operation the same limit as was obtained in one year of operation in the previous experiment at the ILL reactor at Grenoble.

The original proposal was focused on the design of an ANS-based experiment in which a very high neutron flux and large liquid-deuterium cold moderators would have allowed a gain in the discovery potential of a factor of ~10,000 relative to the ILL-Grenoble experiment. After the demise of the ANS project, the studies were redirected towards various alternative neutron sources which may become available at ORNL in the future. These include the HFIR (following a major upgrade to a heavy water reflector and an ANS-type cold moderator) and the proposed Spallation Neutron Source (SNS). Since the average steady neutron flux at HFIR will be considerably higher than that at the SNS, the effort has been focused on designing an experiment for the HFIR HB-2 radial beam, both with and without the heavy water upgrade. New plans of the Laboratory in early 1996 to convert the HB-2 beam line into a thermal neutron scattering facility forced us again to refocus our efforts, this time toward the HFIR HB-3 beam with its smaller opening and with a discovery potential which is a factor of ~300 (per operation-year) higher than that of the ILL-Grenoble experiment. Studies of this option resulted in a Letter of Intent to ORNL to construct and operate a detector at HFIR for an $n \rightarrow \bar{n}$ search. Preparation of a proposal to DOE requesting funding for the experiment will proceed in the future by members of a new N-N Collaboration created during the course of this project.

During March 28-30, 1996, we conducted at Oak Ridge an International Workshop on the Future Prospects of Baryon Instability Searches in p-Decay and in $n \rightarrow \bar{n}$ Oscillation Experiments. The workshop was attended by more than 70 physicists from the U.S., Europe, Russia, China, and Japan. The concept of a new reactor-based experiment at HFIR was presented in 11 talks at national and international meetings. Eight publications for proceedings were prepared. This project has stimulated in part the ongoing ORNL development of a solid pelletized methane cold moderator. As a spin-off from this work, a new original idea of searching for the signal of baryon instability in the traces of rare long-lived isotopes in nonradioactive deep-mined ores has been proposed.

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1. University of Tennessee, Knoxville.
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3. ORNL Computational Physics and Engineering Division.
4. ORNL Engineering Technology Division.
5. Lockheed Martin Energy Systems Engineering Division.
6. ORNL Neutron Science Program Office.

SEARCH FOR TECHNETIUM IN NATURAL TIN METALLURGICAL RESIDUES

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Yu. A. Kamyshkov,[3] A. J. Mattus,[2] G. W. Parker,[2] F. Plasil

Contemporary physics concepts imply that ordinary matter is not stable. Considerable efforts are being presently undertaken by several research groups in the world to establish such instability at the experimental level. The manifestation of this instability can be either proton decay or the transformation of neutrons into antineutrons. If such a transformation occurs inside a nucleus, it might result in a spallation process with a typical mass loss of 10-20 amu. Thus, tin (Z = 52) nuclei located in natural deep nonradioactive deposits may be transmuted to long-lived isotopes of technetium (with Z = 42 and A = 97, 98, and 99) as a result of intranuclear neutron-antineutron transitions.

The new approach relies on the observation of traces of technetium isotopes in remnants of metallurgically processed tin ores. Based on common smelting recovery processes, Tc and its homolog Re are expected to concentrate as oxides in certain furnace residues (flue dust) from which they can be readily extracted. The extraction technique developed for rhenium is planned to be used in an attempt to obtain the first separation of technetium produced by these natural processes.

The goal of the project is, first, to locate a tin mine with deep tin deposits and with low concentrations of radioactive elements and, second, to establish an industrial process of inexpensive by-product extraction of technetium isotopes. Chemical processes can be used for the initial separation of the base element and also for the concentration of the residues. In a final step, the detection of single atoms of chosen isotopes with a typical efficiency, ~1% in milligram samples, will need to be performed by laser-selective photoionization spectroscopy methods. For technetium isotopes a detection limit of $5 \cdot 10^6$ atoms and an efficiency of 0.4% have already been experimentally demonstrated. Detection of single atoms of other elements with typical efficiency of 1% have also been achieved.

The discovery potential of the proposed approach for a baryon instability search in neutron-antineutron transitions is shown in Fig. 3.19 where it is expressed in metric tons of initial tin needed to be processed in order to establish the excess technetium concentration signal over the background level as 2.3 sigma (90% CL) of statistical fluctuation of the background. This result was obtained by calculations that included the estimates of background technetium production by cosmic muons, by spontaneous uranium fission, and by solar neutrinos.

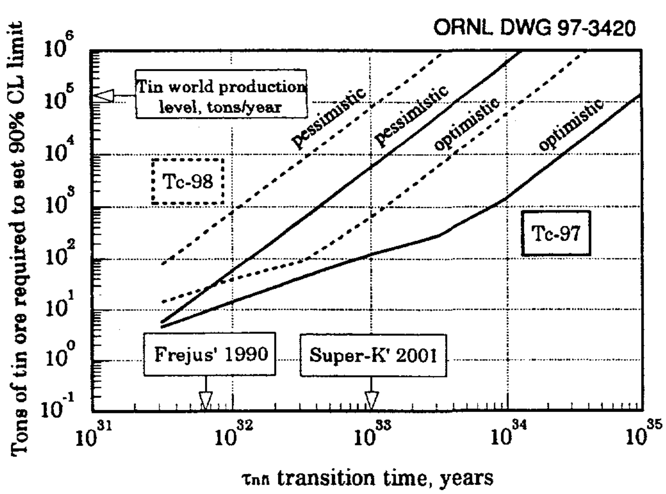

Fig. 3.19. Discovery potential of intranuclear $n - \bar{n}$ transition search by the rare isotope method. "Optimistic" and "pessimistic" assumptions are used for background calculations.

1. University of Tennessee, Knoxville.
2. ORNL Chemical Technology Division.
3. Consultant under subcontract from the University of Tennessee, Knoxville.

ABSTRACTS OF PAPERS PUBLISHED OR SUBMITTED FOR PUBLICATION

RELATIVISTIC HEAVY-ION COLLISIONS

SEARCH FOR DIRECT PHOTON PRODUCTION IN 200 A GeV S+Au REACTIONS: A STATUS REPORT[1]

WA80 Collaboration
(For a complete list of authors, see Ref. 1.)

Direct thermal photons in the p_T range of 0-5 GeV/c are expected to provide a sensitive probe of the hot dense matter formed in the early stage of relativistic heavy-ion collisions. The production of single photons in 200 A GeV S+Au reactions has been investigated using the 3800 element Pb-glass calorimeter of CERN experiment WA80. Neutral π^0 and η cross sections have been measured via their two-photon decay branch yields. In a first analysis of the WA80 results, a slight excess photon yield above that which may be accounted for by hadronic decays was observed for central collisions. A report on the status of the reanalysis of this data is presented.

1. Abstract of published paper: *Nucl. Phys. A* **590**, 81c (1995).

BOSE-EINSTEIN CORRELATIONS OF SOFT PIONS IN ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS[1]

WA80 Collaboration
(For a complete list of authors, see Ref. 1.)

A detailed analysis of pair correlations of positive pions in the target rapidity region is presented. Data on 200 A GeV nuclear collisions were measured with the Plastic Ball in the WA80 experiment at the CERN SPS. The correlation functions are compared with analytical functions and with simulations incorporating Bose-Einstein symmetrization, final-state interactions, and detector resolution. Source radii are shown to increase with increasing target size and with centrality. For central collisions the radii are larger than the geometrical sizes of the involved nuclei.

1. Abstract of published paper: *Z. Phys. C* **69**, 67 (Dec. 1995).

AZIMUTHAL CORRELATIONS IN THE TARGET FRAGMENTATION REGION OF HIGH ENERGY NUCLEAR COLLISIONS[1]

WA80 Collaboration
(For a complete list of authors, see Ref. 1.)

Results on the target mass dependence of proton and pion pseudorapidity distributions and of their azimuthal correlations in the target rapidity range $-1.73 < \eta < 1.32$ are presented. The data have been taken with the Plastic Ball detector setup for 4.9-GeV p+Au collisions at the Berkeley Bevalac and for 200 A GeV/c p-, O-, and S-induced reactions on different nuclei at the CERN SPS. The yield of protons at backward rapidities is found to be proportional to the target mass. Although protons show a

typical "back-to-back" correlation, a "side-by-side" correlation is observed for positive pions, which.increases both with target mass and with impact parameter of a collision. The data can consistently be described by assuming strong rescattering phenomena including pion absorption effects in the entire excited target nucleus.

1. Abstract of published paper: *Phys. Lett. B* **381**, 29 (1996).

PRODUCTION OF η MESONS IN 200 A GeV/c S+S AND S+Au REACTIONS[1]

WA80 Collaboration
(For a complete list of authors, see Ref. 1.)

Minimum bias production cross sections of η mesons have been measured in 200 A GeV/c S+Au and S+S collisions at the CERN SPS by reconstructing the $\eta \rightarrow \gamma\gamma$ decay. The measurements have been made over the rapidity range $2.1 \leq y \leq 2.9$ using the lead-glass spectrometer of WA80. Within the statistical and systematical uncertainties the spectral shapes of π^0 and η mesons yields are identical when their invariant differential cross section is plotted as a function of the transverse mass. The relative normalization of the η to π^0 transverse mass spectra is found to be 0.53 ± 0.07 for S+Au and 0.43 ± 0.15 for S+S reactions. Extrapolation to full phase space leads to an integrated cross section ratio of η to π^0 mesons of 0. 147 ± 0.017 (stat.) ± 0.015 (syst.), and 0.120 ± 0.034 (stat.) ± 0.022 (syst.) for S+Au and S+S collisions, respectively.

1. Abstract of published paper: *Phys.Lett. B* **361**, 14 (1995).

LIMITS ON THE PRODUCTION OF DIRECT PHOTONS IN 200 A GeV ^{32}S+Au COLLISIONS[1]

WA80 Collaboration
(For a complete list of authors, see Ref. 1.)

A search for the production of direct photons in S + Au collisions at 200 A GeV has been carried out in the CERN WA80 experiment. For central collisions the measured photon excess at each p_T, averaged over the range $0.5 \leq p_T \leq 2.5$ GeV/c, corresponded to 5.0% of the total inclusive photon yield with a statistical error of $\sigma_{stat} = 0.8\%$ and a systematic error of $\sigma_{syst} = 5.8\%$. Upper limits on the invariant yield for direct photon production at the 90% C.L. are presented. Possible implications for the dynamics of high-energy heavy-ion collisions are discussed.

1. Abstract of published paper: *Phys. Rev. Lett.* **76**, 3506 (May 1996)

SOFT PHOTON PRODUCTION IN CENTRAL 200-GeV/NUCLEON ^{32}S + Au COLLISIONS[1]

WA93 Collaboration
(For a complete list of authors, see Ref. 1.)

Inclusive photons down to low transverse momena have been measured in 200-GeV/nucleon ^{32}S + Au collisions at the CERN SPS. Data were taken in the WA93 experiment using a small acceptance BGO detector with longitudinal segmentation. The results are compared to WA80 measurements for the same system and results from hadron decay calculations.

1. Abstract of paper to be published in *Physical Review C.*

PHOTON PAIRS FROM RELATIVISTIC HEAVY-ION COLLISIONS AND THE QUARK HADRON PHASE TRANSITION[1]

Dinesh Kumar Srivastava,[2] Bikash Sinha,[3] T. C. Awes

A search for photon pairs produced from the annihilation of quarks and of pions in relativistic heavy-ion collisions may provide confirmation of a quark hadron phase transition. If there is no phase transition, the resulting high temperatures could lead to a much larger production of large mass pairs from pion annihilation, and may even carry a clear signature of kaon annihilation.

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1. Abstract of paper to be published in *Physics Letters B*.
2. Variable Energy Cyclotron Centre, Calcutta, India
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MEASUREMENT OF DIRECT PHOTONS IN CERN EXPERIMENTS WA80/WA98[1]

F. Plasil
(For the WA80 and WA98 Collaborations)

Results from measurements of photons in reactions of 200-GeV/nucleon ^{32}S ions with Au nuclei are presented. A photon excess corresponding to 5% of the total inclusive photon yield is observed in central collisions with a systematic error of 5.8%. Upper limits on the yield for direct photon production at the 90% confidence level are presented. Preliminary results from photon measurements in reactions of Pb+Pb at 158-GeV/nucleon are shown.

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1. Abstract of paper to be published in Proceedings of the International Conference on Nuclear Physics at the Turn of the Millennium: "Structure of Vacuum and Elementary Matter," Wilderness/ George, South Africa, Mar. 10-16, 1996

PHYSICS AND EXPERIMENTS AT RHIC[1]

Glenn R. Young

The Relativistic Heavy Ion Collider (RHIC), under construction at Brookhaven National Laboratory, will be the site of a series of experiments seeking to discover the quark-gluon plasma and elucidate its properties. Several observables should exhibit characteristic behaviors if a quark-gluon plasma is indeed created in the laboratory. Four experiments are now under construction for RHIC to measure certain of these observables over kinematic ranges where effects due to quark-gluon plasma formation should be manifest.

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1. Proceedings of the International Nuclear Physics Conference (INPC'95), Beijing, China, Aug. 21-26, 1995, p. 698, World Scientific Publishing, Singapore, 1996.

FUNDAMENTAL PHYSICS

PROSPECTS FOR NEUTRON-ANTINEUTRON TRANSITION SEARCHES[1]

Yu. A. Kamyshkov,[2] W. M. Bugg,[3] H. O. Cohn,[3] G. T. Condo,[3]
Yu. V. Efremenko,[2] S. K. Lamoreaux,[4] R. A. Lillie,[5] F. Plasil, S. Raman,
M. J. Rennich,[6] K. D. Shmakov,[3] R. Wilson,[7] G. R. Young

An ORNL-UTK-UW-Harvard group is exploring the possibility of performing a new experiment to search for neutron-antineutron transitions either at the ORNL HFIR reactor or at a new proposed neutron spallation source. The advanced layout, based on a large mirror focusing reflector, proposed for this experiment should allow improving the discovery potential of an $n \rightarrow \bar{n}$ transition search by 3-4 orders of magnitude, as compared to the most recent similar experiment at ILL-Grenoble. It should be possible to establish a limit for the characteristic transition time of $\tau_{n\bar{n}} > 10^{10}$ seconds.

1. Abstract of published paper: *Nucl. Phys.* B **48**, 460 (1996).
2. Consultant under subcontract from the University of Tennessee, Knoxville.
3. University of Tennessee, Knoxville.
4. University of Washington, Seattle.
5. ORNL Computational Physics and Engineering Division.
6. Lockheed Martin Energy Systems Engineering Division.
7. Harvard University, Cambridge, MA.

USE OF COLD SOURCE AND LARGE REFLECTOR MIRROR GUIDE FOR NEUTRON-ANTINEUTRON OSCILLATION SEARCH (PROPOSAL)[1]

Yu. Kamyshkov,[2] W. Bugg,[3] H. Cohn,[3] G. Condo,[3] Yu. Efremenko,[2]
S. Lamoreaux,[4] R. Lillie,[5] F. Plasil, S. Raman, M. Rennich,[6]
K. Shmakov,[3] R. Wilson,[7] G. R. Young

An ORNL-UTK-UW-Harvard group is exploring the possibility of performing a new experiment to search for neutron-antineutron oscillations either at the ORNL HFIR reactor or at the proposed neutron spallation source. The advanced layout, based on a large mirror focusing reflector, proposed for this experiment should allow improving the discovery potential of an $n \rightarrow \bar{n}$ transition search by 3-4 orders of magnitude, as compared to the most recent similar experiment at ILL-Grenoble, and to reach the limit of the characteristic transition time of $\tau_{n\bar{n}} > 10^{10}$ seconds. Use of a cold neutron moderator operating at temperatures lower than conventional moderators can futher enhance the discovery potential of an $n \rightarrow \bar{n}$ search provided that neutrons can be thermalized at these lower temperatures. The latter assumption is an open question.

1. Abstract of paper to be published in Proceedings of the 13th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-M), Oct. 11-14, 1995, Villigen, Switzerland.
2. Consultant under subcontract from the University of Tennessee, Knoxville.
3. University of Tennessee, Knoxville.
4. University of Washington, Seattle.
5. ORNL Computational Physics and Engineering Division.
6. Lockheed Martin Energy Systems Engineering Division.
7. Harvard University, Cambridge, MA.

PROSPECTS FOR BARYON INSTABILITY SEARCH WITH LONG-LIVED ISOTOPES[1]

Yu. Efremenko,[2] W. Bugg,[3] H. Cohn,[3] Yu. Kamyshkov,[2] G. Parker,[4] F. Plasil

In this paper we consider the possibility of observation of baryon instability processes occurring inside nuclei by searching for the remnants of such processes that could have been accumulated in nature as rare long-lived isotopes. As an example, we discuss here the possible detection of traces of ^{97}Tc, ^{98}Tc, and ^{99}Tc in deep-mined nonradioactive tin ores.

1. Abstract of paper to be published in Proceedings of International Workshop on Future Prospects of Baryon Instability Search in p-Decay and $n \to \bar{n}$ Oscillation Experiments, Oak Ridge, TN, Mar. 28-30, 1996.
2. Consultant under subcontract from the University of Tennessee, Knoxville.
3. University of Tennessee, Knoxville.
4. ORNL Chemical Technology Division .

PROSPECTS FOR NEUTRON-ANTINEUTRON TRANSITION SEARCH[1]

Yu. Kamyshkov[2]

Presently available sources of free neutrons can allow an improvement in the discovery potential of a neutron-antineutron transition search by four orders of magnitude as compared to that of the most recent reactor-based search experiment performed at ILL in Grenoble.[3] This would be equivalent to a characteristic neutron-antineutron transition time limit of $>10^{10}$ seconds. With future dedicated neutron-source facilities, with further progress in cold-neutron-moderator techniques, and with a vertical experimental layout the discovery potential could ultimately be pushed by another factor of ~100 corresponding to a characteristic transition time limit of $\sim 10^{11}$ seconds. Prospects for, and relative merits of, a neutron-antineutron oscillation search in intranuclear transitions are also discussed.

1. Abstract of paper to be published in Proceedings of International Workshop on Future Prospects of Baryon Instability Search in p-Decay and $n \to \bar{n}$ Oscillation Experiments, Oak Ridge, TN, Mar. 28-30, 1996.
2. Consultant under subcontract from the University of Tennessee, Knoxville.
3. M. Baldo-Ceolin et al., *Z. Phys. C* **63**, 409 (1994).

NEUTRON-ANTINEUTRON OSCILLATION[1]

Yu. Kamyshkov[2]

The aim of this talk is to review the current status of and the future prospects for an experimental neutron-antineutron transition search. Traditional and new experimental techniques are discussed. In the $n \to \bar{n}$ search in experiments at existing reactors, it would be possible to increase the discovery potential up to four orders of magnitude for vacuum $n \to \bar{n}$ transitions relative to the existing experimental level or to achieve the limit of $\tau_{n\bar{n}} > 10^{10}$ s. With dedicated future reactors and ultimate experimental layout, it might be possible to reach the limit of 10^{11} s. The progress in an intranuclear transition search expected to be made in the next decade by the SuperKamiokande and Icarus detectors can be matched in an approach where long-lived isotopes in deep-mined ores are searched.

1. Abstract of paper to be published in Proceedings of 1996 DPF/DPB Summer Study on New Directions for High-Energy Physics (Snowmass 96), Snowmass, CO, June 25-July 12, 1996.
2. Consultant under subcontract from the University of Tennessee, Knoxville.

PROSPECTS OF A BARYON INSTABILITY SEARCH IN NEUTRON-ANTINEUTRON OSCILLATIONS[1]

Yu. Efremenko[2] and Yu. Kamyshkov[2]

The purpose of this article is to review the current status and the future prospects for an experimental neutron-antineutron transition search. Traditional and new experimental techniques are discussed here. In the $n \rightarrow \bar{n}$ search in experiments at existing reactors, it would be possible to increase the discovery potential up to four orders of magnitude for vacuum $n \rightarrow \bar{n}$ transitions relative to the existing experimental level or to achieve the limit of $\tau_{n\bar{n}} \sim 10^{10}$ s. With dedicated future reactors and an ultimate experimental layout, it might be possible to reach the limit of 10^{11} s. Significant progress in an intranuclear $n \rightarrow \bar{n}$ transition search is expected to be made during the next decade by the SuperKamiokande and Icarus detectors. It can be matched, or even exceeded, in a new alternative approach, where unstable long-lived isotopes of technetium are searched in nonradioactive deep-mined ores.

1. Abstract of paper to be published in Proceedings of 1996 DPF/DPB Summer Study on New Directions for High-Energy Physics (Snowmass 96), Snowmass, CO, June 25-July 12, 1996.

2. Consultant under subcontract from the University of Tennessee, Knoxville.

PROSPECTS FOR A NEUTRON → ANTINEUTRON TRANSITION SEARCH AT A REACTOR OR SPALLATION SOURCE[1]

H. O. Cohn[2]

Our collaboration[3] is exploring the possibility of performing a new experiment to search for neutron-antineutron transitions either at the ORNL HFIR reactor or at a new proposed neutron spallation source. The advanced layout, based on a large mirror focusing reflector, proposed for this experiment should allow improving the discovery potential of an $n \rightarrow \bar{n}$ transition search by 3-4 orders of magnitude, as compared to the most recent similar experiment at ILL-Grenoble. It should be possible to establish a limit for the characteristic transition time of $\tau_{n\bar{n}} > 10^{10}$ seconds.

1. Abstract of paper to be published in Proceedings of the Symposium on the Savannah River Accelerator Project and Complementary Spallation Neutron Sources," Columbia, SC, May 14-15, 1996.

2. University of Tennessee, Knoxville.

3. Neutron-Antineutron Collaboration: Oak Ridge National Laboratory, University of Tennessee, University of Washington, Harvard University, Moscow Institute of Nuclear Research, Moscow Institute for Theoretical and Experimental Physics, Tsinghua University.

4. ATOMIC PHYSICS

OVERVIEW

The principal activities of the atomic physics program are threefold: atomic collisions research, atomic data compilation, and advanced plasma diagnostic development. The atomic collision physics research can be broadly characterized in two parts: accelerator-based atomic physics and atomic collisions of low-energy, highly charged ions as supplied by an ECR source.

The scientific objective of the accelerator-based atomic physics program is development of detailed understanding of the interactions of charged and neutral atoms and molecules with electrons, atoms, surfaces, and solids through investigations employing beams of particles accelerated to high energies. Facilities at ORNL used for the experimental phase of this research include the EN Tandem Van de Graaff and the Holifield Radioactive Ion Beam Facility (HRIBF). Off-site facilities such as the Tandem Accelerator Super-Conducting Cyclotron (TASCC) at Chalk River, Canada, and the Super Proton Synchrotron (SPS) at CERN, Geneva, Switzerland, are also used to extend the range of energies examined. Electron-molecular ion interactions are being studied at the CRYRING heavy-ion storage ring in Stockholm, Sweden. Taken together, these facilities permit measurements over a range of collision energies from milli-electron volts to tens of terra-electron volts, a span of sixteen orders of magnitude, from thermal to ultrarelativistic. Present focii of interest include, at the high-energy end, atomic collisions of ultrarelativistic lead ions (33 TeV) which leads to pair production and to electron capture from pairs. Also of interest is a new effect, the reduction of stopping power due to nuclear size effects. At the low energy end, dissociative recombination of molecular ions such as H_3^+ and HeH^+ are studied down to energies of 10^{-4} eV using storage ring techniques with ~20-MeV ions. The results here have direct impact on astrophysical models.

The goal of the ECR-based program is improved understanding of the collisional interactions of low-energy molecular and atomic ions (singly and multicharged) with electrons, atoms, ions, and surfaces. A major part of the program focuses on collision systems found in the edge and divertor plasma of present and future magnetically confined fusion devices that are important in determining, e.g., ionization balance, and energy and particle transport, or the interpretation of edge plasma diagnostics. A crossed beams approach is applied to cross-section measurements for ionization of multicharged ions, and for dissociation of molecular ions, both by electron impact. A collaborative electron-ion merged-beams experiment is underway to measure cross sections for electron-impact excitation of multiply charged ions by electron energy-loss spectroscopy. Merged beams are also being used to study charge exchange and ionization collisions of multiply charged ions with hydrogen (deuterium) atoms at very low kinetic energies. Analysis of ejected electrons and scattered ions is being performed to study the interaction of low multiply charged ions with solid surfaces. The theoretical effort has focused on the development of new techniques for the calculation of heavy particle and electron collision processes such as charge transfer, elastic scattering, and electron impact excitation or ionization that are either of fundamental interest or needed in support of modeling or simulation efforts in the magnetically confined fusion program. This theoretical work is closely coordinated with the activities of the Controlled Fusion Atomic Data Center (CFADC). The plasma diagnostics program concentrates on the development of advanced diagnostics for magnetic fusion experiments. The current emphasis is on the development of a collective Thomson scattering diagnostic to measure density and velocity distributions of alpha particles, and of a far-infrared Faraday rotation diagnostic for measuring electron density and temperature profiles.

EXPERIMENTAL ATOMIC PHYSICS

POSITRON PRODUCTION IN COULOMB COLLISIONS OF 33-TeV Pb IONS

C. R. Vane, H. F. Krause, and S. Datz

At ultrarelativistic energies, atomic collisions between heavy, highly charged atoms produce extremely intense, rapidly varying electromagnetic fields which, in turn, give rise to very large ionization cross sections, diminished electron capture cross sections, and copious lepton-pair formation. Recent progress toward realization of energetic ion-ion colliders such as the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory and the Large Hadron Collider (LHC) at CERN has sparked renewed interest in electromagnetic phenomena at very high energies. These heavy-ion collisions are fundamentally different from those historically receiving attention involving singly charged projectiles because the coupling constant, $Z\alpha$, can be large (≥ 0.5) in heavy systems. Lepton-pair production in these systems is especially interesting because the collision strength can be varied continuously, from regions of low charge and energy, where past applications of low-order perturbative methods are suitable, to higher energy and charge regimes where first-order perturbative calculations are known to occasionally give unphysical results, and non-perturbative methods will be required.

In a recent paper,[1] we reported results of measurements of electrons and positrons formed as pairs in peripheral collisions of ultrarelativistic sulfur ions with thin solid targets. Those data gave experimental angular and momentum differential cross sections for electrons and positrons which agreed relatively well with predictions of lowest-order perturbative calculations. This agreement was expected for 6.4-TeV sulfur ions, since the calculated probabilities for pair production were relatively small at all impact parameters. It was noted in Ref. 1 that failure of perturbative calculations might be anticipated for significantly heavier collision systems and at higher impact energies, in which low-order perturbation terms would give pair production probabilities violating unitary at sufficiently small impact parameter. Several theoretical treatments have concluded that multiple pairs should be formed in single close collisions, with some disagreement as to the effect of the multiple-pair forming channels on total cross sections. Both perturbative and non-perturbative calculations have lead to predictions of Poisson distributions for the number distributions of multiple electron pairs.[2,3]

We have measured 1–12-MeV/c positrons emitted in collisions of 33-TeV Pb^{82+} ions from the CERN SPS accelerator facility with thin targets of $(CH_2)_x$, Al, Pd, and Au and searched for evidence of multiple-pair formation. Positron $d\sigma/dp+$ distributions obtained for Pb ions are similar to those measured previously for 6.4-TeV S ions, but exhibit an enhanced cross section at very low momentum (<2 MeV/c) and at high momentum (>8 MeV/c) for Pb ions. Integrated yields of positrons were found to scale as $Z_P^2 Z_T^2$ (where Z_P and Z_T are the projectile and target charges), as predicted by perturbative treatments. A significant electronic cross-talk background, along with low counting statistics of multiple-pairs, set the uncertainty of our measurements. Detailed analyses have been completed which set upper limits on the ratios of multiple- to single-pairs assuming Poisson N-pair production distributions (as predicted by most theories). These analyses assume complete independence of momentum distributions of any multiple positrons. For 6.4-TeV S + Au collisions, we found previously that single-pair electrons and positrons exhibited such independence. Under the above assumptions and constraints, we find that 2% (+4%-2%) of positrons from Pb + Au (1–1/2 MeV/c) arise from multiple-pair formation. A number of theoretical treatments predict significant formation of multiple pairs of electrons and positrons in single, peripheral, collisions of heavy ions and targets at ultrarelativistic energies. Calculations have been performed by Guclu et al.[2] for the specific collision conditions reported here. The theoretical results exhibit a two-pair target atomic number (Z_T^4) behavior, with multiple pairs being negligible for low-Z_T $(CH_2)_x$ and Al) and contributing ~2.5% of all pairs produced for Pb + Au. Our measurements agree with these results. Calculations by Alscher et al.[3] predict larger contributions from multiple-pairs, ~5% for Pb + Au at 33 TeV, again – lying within our experimental error.

1. C. R. Vane et al., *Phys. Rev. A* **50**, 2313 (1994).
2. M. C. Güclu et al., *Phys. Rev. A* **51**, 1836 (1995).
3. A. Alscher et al., DOE/ER/40561-264-INT96-00-126.

ELECTRON CAPTURE AND LOSS FROM PAIR PRODUCTION BY 33-TeV Pb IONS

H. F. Krause, C. R. Vane, and S. Datz

In Coulomb collisions at sufficiently high energies, highly charged ions can readily excite or ionize electrons from the negative energy continuum into observable atomic bound states of the ion or into states of the positive continuum. The cross sections grow with collision energy, and at ultrarelativistic energies, the capture from pair production mechanism dominates all others for all targets. The predicted capture cross section for 33 TeV Pb^{82+} on Au, for example, has been calculated to be 50 barns via this pair production mechanism.[1] Other competing capture mechanisms such as nonradiative capture and radiative electron capture have significantly smaller cross sections of 0.4 and 1.2 barns for the same system.[2]

The experiments were performed by inserting solid targets of varying thicknesses into the Pb^{82+} beam about 0.8 Km upstream of a particle detector. The H3 beam line at the CERN Super Proton Synchrotron near Geneva, Switzerland, was used as a magnetic spectrometer to disperse the Pb^{82+} primary beam from the Pb^{81+} beam leaving the target. The beam line has numerous electro-optic beam elements such as quadrapoles to prevent loss of ions along the long beam line.

We have completed detailed analyses of charge-changing data obtained at the CERN SPS accelerator facility in 1995 for 33-TeV Pb ions passing through targets of C, Al, Cu, and Au. These data yield equilibrium fractions ~0.8×10^{-3} of one-electron ions which agree with theoretical calculations for electron capture and ionization for heavy targets (Cu and Au), but are substantially higher than predictions for light targets (C and Al) ~(1.5×10^{-3}). This suggests that capture into excited states is a substantial fraction of total capture. Ionization of excited states in heavy targets is probable because stripping rates of $n \geq 2$ electrons are competitive with radiative stabilization rates. In light targets (or in gases) excited states decay to Pb^{81+}(1s) and may lead to significant enhancement of total capture. This is especially important for colliders where essentially all excited states will survive to form one-electron ions which are lost from storage. We obtain a total capture cross section for Pb + Au of 75 ± 25 barns, 72 barn of which is attributed to capture from pair production. Current theoretical calculations yield a Pb^{81+}(1s) capture cross section of 50 b. The measured effective electron loss cross section for Pb^{81+} + Au is 81 kbarn. Calculated cross sections for Pb^{81+}(1s) from Ref. 2 amount to 61 kbarn. Background contributions of Pb^{81+} arising from collisions with upstream air and beamline windows limited the accuracy of these measurements. Future measurements this fall (Nov. 1996) are designed to eliminate these backgrounds and allow more precise determination of both capture and loss cross sections.

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1. M. R. Strayer and J. Wells, private communication.
2. R. Anholt and U. Becker, *Phys. Rev. A* **36**, 4628 (1987).

THE EFFECT OF NUCLEAR SIZE ON MOMENTUM TRANSFER TO ELECTRONS FOR ULTRARELATIVISTIC IONS

S. Datz, H. F. Krause, and C. R. Vane

The slowing down of energetic ions in matter is dominated by momentum exchange with electrons. This is manifested in the energy loss of penetrating ions. Lindhard and Sørensen (LS) performed exact quantum mechanical calculations on the basis of the Dirac equation to produce values for the average energy loss and straggling which are stated to be accurate for any value of projectile charge. Using a point Coulomb potential, they are able to reproduce the results of Bohr, Bethe, Bloch, and Mott. However, they show that at sufficiently high energies the finite nuclear size effects the stopping power. It is convenient to view the projectile nucleus as a stationary scattering point for a flux of electrons moving at the velocity of the ion in the laboratory system. According to LS, an electron will encounter the nucleus when its angular momentum $pR \cong \gamma m_o cR$ where R is the nuclear radius ($R \sim 1.2 \times 10^{-13} A^{1/3}$ cm), where A is the atomic weight). When $pR \sim \hbar/2$ modification of the first few quantum phase shifts will be needed, i.e., nuclear size effects should be important when $2\gamma m_O cR/\hbar = \gamma A^{1/3}/160 \cong 1$. Alternatively, one may consider that the effect will become important when the deBroglie wavelength of the electron, $\lambda = (\hbar/\gamma m_o c)$ becomes comparable to the nuclear size.

We made measurements of dE/dx for 160-GeV A $^{208}Pb^{82+}$ (γ=168) ions, obtained from the SPS facility at CERN, in targets of C, Si, Cu, Sn, and Pb, and compare the results with the predictions of the LS theory. The beam from the CERN SPS accelerator is passed through the targets and is then bent 42 mr by an array of dipoles and is momentum analyzed using a collimator slit ~150 m downstream. After a passage of ~300 m, it is bent again and focused onto a detector ~350 m further downstream. The measured resolution of the system is ~7 x 10^{-4} which permits the location of a peak to be determined with a precision of 1 x 10^{-4}. Four targets of each element mounted on the ladder were selected to give energy losses of approximately 0.1%, 0.2%, 0.4%, and 0.8% of the primary beam energy.

The measured stopping powers were (in MeV/mg/cm^2) 15.20 for C, 15.09 for Si, 13.05 for Cu, 12.38 for Sn, and 11.69 for Pb. The LS prediction of nuclear size effect is confirmed. For low target Z_2 such as C and Si, the agreement is within experimental error (±1%). However, there is a drift toward higher stopping power in Cu and Sn and a definite deviation in the case of the Pb target.

NOVEL APPARATUS AND METHODS FOR PERFORMING REMOTELY CONTROLLED EXPERIMENTS AT CERN

H. F. Krause, E. F. Deveney, N. L. Jones, C. R. Vane, and S. Datz

Recent atomic physics studies[1-2] involving ultra-relativistic Pb ions (160 GeV/nucleon) required solid target positioners, scintillators and a sophisticated data acquisition and control system installed in a remote location at the CERN Super Proton Synchrotron near Geneva, Switzerland. The apparatus, installed in a high-radiation zone underground, had to (i) function for a 2-3 month period, (ii) automatically respond to failures such as power outages and particle-induced computer upsets, and (iii) communicate with the outside world via an existing telephone line. The heart of the apparatus developed was an Apple Macintosh-based CAMAC system that answered the telephone and interpreted and executed remote control commands that (i) sensed and set targets, (ii) controlled voltages and discriminator levels for scintillators, (iii) modified data acquisition hardware logic, (iv) reported control information, and (v) automatically synchronized data acquisition to the CERN spill cycle via a modem signal and transmitted experimental data to a remote computer.

Our experiment was on the same beam line as WA98 so we had to ensure removal of all elements of our operation before the next WA98 experiment. Because the apparatus could not be approached during the entire beam time, our targets had to be automatically extracted from the beam under gravity during power failures, a computer crash or in the event of a total electronics failure so that the WA98 experiment would not be compromised. Electronic modules having low-power Schottky chips were used instead of CMOS technology wherever possible to lower the probability of damage from an expected low flux of stray scattered particles at the apparatus site. Our apparatus was simple, portable and capable of being installed quickly during a week shutdown of the SPS.

We have shown that a sophisticated scientific apparatus controlled by a desktop computer can be made to function in a very harsh remote environment for months. A watch-dog circuit is a practical method for keeping the remote scientific apparatus functioning throughout this long period of time. In addition, our experience shows that the electronic and computer equipment doesn't have to be radiation "hardened" where there is a substantial gamma ray background (10-20 mrem/hr, gamma-ray background when the SPS was not operating and much higher during SPS operation) and where the energetic particle beam current is below 10^6/s. Our experience also proves that it is practical to synchronize simple data acquisition functions in the remote system to outside world real-time events within tens of millisec using 1200-baud serial communications. This scientific equipment has allowed us to economically perform new high-energy atomic physics experiments by parasitically using large scale equipment built for high energy physics experiments at CERN. We have used our apparatus successfully within the Geneva telephone exchange and intercontinentally (Bell South/ATT – Geneva exchange); the byte error rates in data transmission were lower than 10^{-4} (sensitivity of a controlled test) at 1200 baud in both cases. This experience proves that long-distance telephone-based "virtual experiments" are feasible, even where scientific equipment is operating in a vary harsh environment. Our successful "virtual laboratory" approach that uses off-the-shelf electronics, is generally adaptable to more conventional bench-type experiments.

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DISSOCIATIVE RECOMBINATION

S. Datz

A number of new aspects of dissociative recombination (DR) have been uncovered in the last year using the CRYRING facility in Stockholm, Sweden. These include measurements of H_3^+, H_2D^+ including absolute cross sections, branching (e.g., three-body versus two-body) and isotope effects. Also a relation of DR of H_2 + D to the cosmic abundance of deuterium has been developed. We have measured dissociative recombination (DR) in H_2D^+, and H_3^+. The cross sections were measured over an energy range from 0.001 to 25 eV and are similar except in the region above ~3 eV where "direct" processes dominate where the H_2D^+ cross sections are approximately four times smaller than those for H_3^+. The two-body fraction for $H_2D^+ + e \rightarrow H_2 + D$ or HD+H shows much the same behavior as is found for $H_3^+ + e \rightarrow H_2 + H$. At $E_{rel} < 0.1$ eV, the two-body fraction is somewhat higher for H_2D^+, e.g., for H_3^+ at relative energy of 4 eV, the value is 0.65 as against ~0.9 for H_2D^+, at the same energy. An isotope effect in the two-body channel for H_2D^+ is observed giving a product ratio of $HD/H_2 \equiv 2.5$ over the entire range.

Deuterated molecules in interstellar clouds constitute a unique source of information on three interstellar parameters: the deuterium/hydrogen abundance ratio [D]/[H], the fractional ionization in dense clouds and the galactic ionizing flux. The molecular ion H_2D^+ plays a key role in the formation of deuterated molecules. Dissociative recombination with electrons is a major loss channel and a potential source of deuterium atoms. With the data obtained, H+H+D, HD+H, and H_2 + D of the cloud L1529, we derive from observational data on HCO^+ an upper limit to the fractional ionization of 2×10^{-6}, a [D]/[H] ratio of 1.7×10^{-5} and an atomic D/H ratio of 2.7×10^{-3}.

Absolute cross sections have been determined for the dissociative recombination and dissociative excitation of $^4HeH^+$ for electron energies below 40 eV. The cross section is in semi-quantitative agreement with recent theoretical results by Sarpal et al. and Guberman. The calculated resonant structure below a collision energy of 1 eV was not fully reproduced by the experiment. The development of a technique in which arrival of two neutral fragments and their spatial separation at the detector can be measured now permits the determination of final state information, e.g., in the case of $HeH^+ + e \rightarrow He + H$ at ~0 kinetic energy. We find that the H atoms is exclusively formed in the n=2 state (Lyman α emission from space is an often used marker). Dissociative recombination products at 0 eV collision energy have been determined; ground state helium and excited hydrogen atoms (n=2) are dominantly formed, in agreement with recent predictions by Guberman. The dissociative excitation has an onset around 10 eV and follows the shape of the dissociative recombination cross section, illustrating that both processes start with the formation of doubly excited neutral states that lie in the ionization continuum as well as in the dissociation continuum.

Product state information on dissociative recombination (DR) of HD^+ and H_2^+ has been obtained over a wide range of electron energies. It is concluded that at low electron energies (<3 eV) hydrogen atoms are formed preferentially in highly excited states (n>2); at high electron energies (>12 eV) both hydrogen fragments are excited. The dissociative recombination rate of H_2^+ in the energy range of 0 eV to 20 eV has been also measured as a function of storage time. The results of both experiments suggest that an H_2^+ beam is still vibrationally excited after 50 s at our experimental conditions. The dissociative recombination rate of H_2^+ (at 100 K electron temperature) decreases significantly due to interaction with the cooler electrons. This is not observed in a similar experiment with HD^+. Two mechanisms are responsible for the DR rate changes; the high vibrational levels ($v \geq 5$) have a very high DR rate. The DR process itself affects their lifetime in the ring. The low vibrational levels may be influenced by superelastic collisions with electrons in the cooler on a longer time scale.

STATUS REPORT OF EN TANDEM OPERATIONS

N. L. Jones and C. R. Vane

During the period since the last progress report, the EN Tandem continued to operate in support of the Accelerator-Based Atomic Physics program. Terminal voltages between 0.38 and 6.0 MV were utilized, accelerating beams of ions from hydrogen through bromine. Elastic scattering of neutrons from a thin lithium target by proton beams was developed. This capability is being developed with the Instrumentation and Controls Division for the purpose of creating neutrons that are mono-energetic at any given angle. Researchers will utilize these neutrons for the development of next-generation neutron health physics instruments. Charging belt development efforts continued. The deeper understanding of charging behavior gained in this study has resulted in improved ripple performance with all types of belt material.

The facility was utilized by ORNL Physics Division staff, by researchers from other ORNL divisions, and by outside users from the University of Connecticut, University of Tennessee, and foreign institutes (i.e., the Royal Institute of Technology, Stockholm, Sweden and Technion – Israel Institute of Technology, Haifa, Israel).

Several runs were conducted for beam monitor and detector development in support of the Holifield Radioactive Ion Beam Facility. The University of Tennessee adjuncts have been developing equipment and methods for the study of low-incident-angle collisions of energetic heavy ions on surfaces. A conical sector electron analyzer capable of simultaneously collecting electron energy spectra at eight positions each separated by 10° was installed in the 180° beam line spectrometer chamber. This spectrometer, designed and built at the A. F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia, was developed under a "Joint NIS-IPP Program" with the US and Russia. The Elbek magnetic spectrometer was refitted for experiments in the study of projectile energy loss in multiply ionizing ion-atom collisions. The method used for this study is unique to this facility.

A NEW CONTROL SYSTEM FOR THE EN TANDEM

N. L. Jones

As part of a recirculating terminal stripper project, an overall upgrade of the accelerator's control systems was required. Development of a robust system that would not be prone to upset from sparks was necessary, and a phased approach was taken. This involves first converting the accelerator's ground potential systems, then ion source (~100 kV) systems that can be easily accessed by merely running down high voltage supplies, and finally terminal potential systems that operate in high pressure gas at potentials exceeding 7 MV.

A major consideration was the Man-Machine Interface (MMI). The system design draws heavily on the 25 URC's combination of assignable shaft encoders, or "virtual knobs," and assignable analog meters. The EN system adds computer graphics screens as depicted in Fig. 4.1 to produce an intuitive interface for both experienced and unseasoned operators.

ORNL-DWG. 97-5489

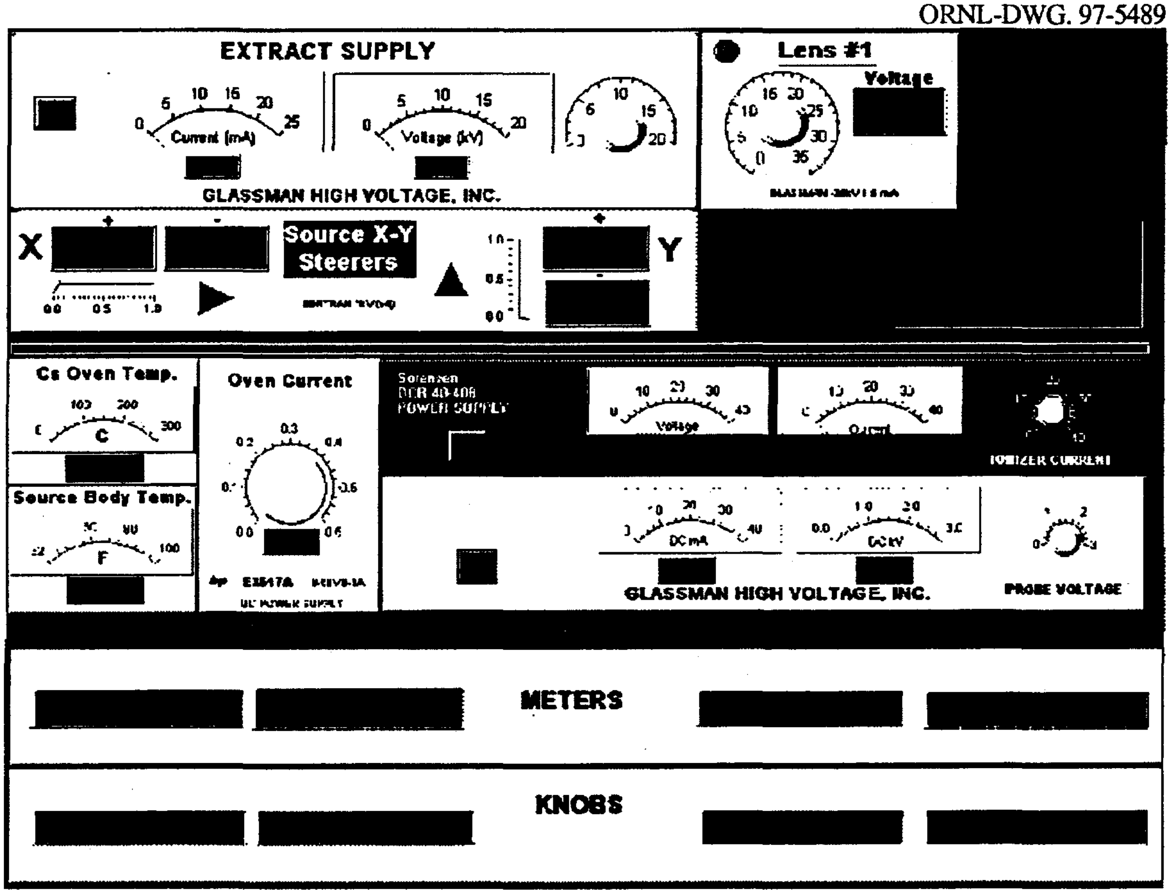

Fig 4.1. Screen capture of the Ion Source controls display.

A Pentium CPU PC runs a control program written in LabVIEW under the Windows 95 operating system. A shared-memory loop interface controller in the PC communicates via single strand plastic fiber optic cables with Device Interfaces containing I/O boards in the field. EMI surge protection utilizes careful signal cable routing, copper shielding, metal oxide varistors, and ferrite cores.

In September 1996, with a total of fifty-nine I/O points serviced by the new system, several experiment runs were conducted with the accelerator. Operator comments were all positive. There is no sensation of response lag, and the controls feel as if hard wired to potentiometers.

EXPERIMENTAL STUDIES OF THE IMAGE-CHARGE ACCELERATION OF CONVOY ELECTRONS PRODUCED IN FAST, GRAZING ION-SURFACE COLLISIONS

R. Minniti,[1] H. Lebius,[1] J. Y. Lim,[1] and S. B. Elston[2]

We use convoy electron emission induced by ions specularly reflected from flat, clean single crystal surfaces to probe the dynamic image potential arising from interaction between the passing ion and surface electronic structure. Convoy electrons, with nearly the same vector velocity as the projectile ion, remain in prolonged proximity to the dynamic image (or surface *wake*), so they provide a particularly sensitive probe. Convoy electrons form a peak in the spectrum of electrons emitted near the forward collision direction; the location and shape of the peak observed from ion-gas and ion-bulk solid collisions have been explained in terms of the underlying ejection mechanisms – electron capture from target bound states to low-lying projectile-centered continuum states and electron loss from projectile bound states to the low-lying projectile continuum – and in terms of the fundamental nature of continuum states interacting with a Coulomb center. In these collisions, convoy electrons are not emitted solely in the Coulomb field of the ion; there is a repulsion from the surface wake potential, which accelerates the convoy electrons and shifts the convoy peak energy as well as deflects the angular emission peak away from the surface plane.

An electron spectrometer equipped with position-sensitive electron detection provides efficient acquisition of detailed multiply differential images of the angular and energy emission distribution. The spectrometer simultaneously images emission from angles over a 12° x 24° range with an energy resolution ~1% FWHM. The use of silicon as a target crystal permits fabrication from wafers selected from commercial product runs and takes advantage of simple surface annealing techniques that employ direct Ohmic heating of the target substrate and that have been developed and characterized using STM technology. Recent measurements have added exit projectile charge state analysis and coincident detection of the scattered projectiles, ensuring collection of emission involving specularly reflected ions only.

Our first measurements[3] emphasize the acceleration and deflection of the convoy peak, but our eventual goal is to quantify other characteristics of the peak shape, which should be indicative of higher-order effects of the dynamic image potential. Carbon projectiles of charge states q = 1+ to 4+ incident on silicon (100) surfaces with collision velocities v ~ 0.3 to 0.5 a.u. and grazing angles of incidence ~0.2° are observed to produce emission shifted toward higher energy by as much as 32% of the isotachic (velocity matched) value at the lower collision velocity, corresponding to an absolute shift of 52 eV above the isotachic position at 164 eV, and deflected from the specular reflection direction by about 3°. Comparison of our results with those of classical trajectory Monte Carlo simulations of the emission process has begun in collaboration with C. O. Reinhold and J. Burgdörfer, and we expect this comparison to guide future choices of projectiles, targets and other collison parameters. An encouraging preliminary sign is that absolute yields determined in the coincidence measurements are in reasonable agreement with an earlier CTMC yield calculated by Reinhold, Burgdörfer, and Japanese co-workers K. Kimura and M. Mannami[4] for the somewhat different collision system of Li ions on SnTe surfaces. Our result is that of the order of one ion in four produces an electron within the main portion of the convoy peak; a more precise statement requires specifying the range of emission angles and energies integrated over, as well as initial projectile charge state and, most likely, target surface structure and orientation. There is evidence in the data that target orientation is a critical unexplored parameter, and we plan to investigate the effects of both small (~few degrees) and large (~180°) variations in target azimuth about the surface normal, in the near future. The final analysis of our coincidence data will provide emission yields, convoy electron peak shifts, and exit projectile charge state and angular distributions. The results show, in agreement with our first, non-coincidence measurements, that the surface wake-induced acceleration of the convoy electron peak depends on incident projectile charge state at the higher collision velocities studied (v ~ 4.5 a.u.), even though the exit charge state distribution measurements show the exit projectiles to have reached charge state equilibrium. The implication, that the projectile ions are not in a state of equilibrated charge at the time of convoy electron production, is borne out by an observed initial charge state dependence of the convoy electron production yield (per exiting ion) as well, at the higher velocity.

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2. Adjunct staff member from the University of Tennessee, Knoxville, TN.
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LOW-ENERGY ATOMIC COLLISIONS

MERGED-BEAMS MEASUREMENTS OF ELECTRON-IMPACT EXCITATION OF MULTICHARGED IONS

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The JILA merged electron-ion beams energy loss (MEIBEL) apparatus was applied in this period to collaborative measurements of cross sections for electron-impact excitation of multiply charged ions at the ORNL ECR Multicharged Ion Research Facility. Particularly emphasized were investigations of cross sections dominated by dielectronic resonance structure, first measured[4] on this experiment for an optically-forbidden transition in Kr^{6+}. The latest measurements[5] were for the optically-forbidden $3s^2\ {}^1S \rightarrow 3s3p\ {}^3P$ transition in Ar^{6+} which exhibited significant disagreement with theoretical predictions.

Also studied during this period was the $2s\ {}^2S \rightarrow 2p\ {}^2P$ transition in C^{3+} for which two previous measurements[6,7] using an optical fluorescence technique are in disagreement over the absolute magnitude of the excitation cross section. Relative cross sections for this transition have been measured using the MEIBEL apparatus and are shown in the figure below along with a normalized curve of close-coupling calculations[8] convoluted with a 0.25 eV Gaussian representing the experimental energy spread of the electron beam. However, the absolute magnitude is still uncertain for these results due to the limited sensitivity of the beam probe to the low energy electrons used. The beam probe, used to measure the physical overlap of the two beams in the interaction region of the experiment, has since been modified with an accelerating grid so that low energy electrons can be accelerated up to 100 eV or so, increasing the sensitivity of the microchannel plate to the electrons. Currently, a systematic study of this modified beam probe is under way in order to permit accurate absolute cross section determinations for the C^{3+} $2s \rightarrow 2p$ transition as well as for future investigations.

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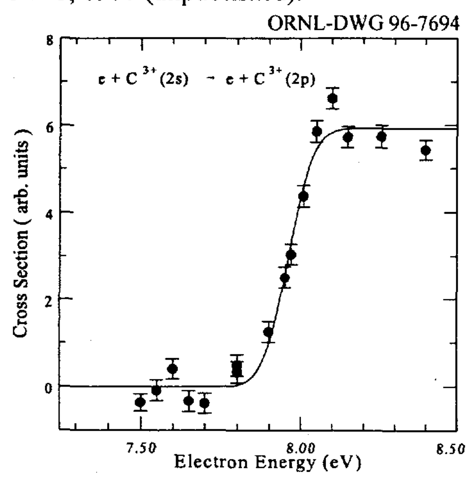

Fig. 4.2. Relative cross sections for electron-impact excitation of C^{3+} ions as a function of center-of-mass energy.

ELECTRON-ION CROSSED BEAMS MEASUREMENTS MULTICHARGED IONS AND MOLECULAR IONS

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The ORNL electron-ion crossed beams experiment was employed during this period to determine the metastable fractions of multicharged ion beams through ionization cross section measurements and to investigate the electron-impact dissociation of simple hydrocarbon molecular ions. In support of the JILA merged electron-ion beams energy-loss (MEIBEL) experiment[5] on the excitation of the $3s^2\ ^1S \rightarrow 3s3p\ ^3P$ transition in Ar^{6+}, the metastable fraction of the Ar^{6+} ion beam from the ORNL ECR ion source was determined by measuring the electron-impact ionization cross sections above and below the ground-state threshold. From the fact that only the metastable Ar^{6+} ions contribute to the cross section below the ground-state threshold, the metastable fraction of the ion beam could be determined to be 0.285. In a similar experiment, the metastable fraction of a C^{4+} ion beam was measured to be 0.05. This measurement supplemented an experiment studying electron capture in C^{4+} + H(D) collisions performed on the ORNL ion-atom merged beams apparatus. The crossed beams experiment also verified the absence of metastables in ion beams used for experiments on low energy electron capture by N^{2+} from atomic hydrogen.[6]

The electron-ion crossed beams apparatus was also used to continue investigations on electron-impact dissociation of hydrocarbon molecular ions. Preliminary measurements on the dissociation of CD^+ producing C^+ demonstrated that the electrostatically confined electron gun used for the last three years was not suitable for electron energies below 50 eV for ions exhibiting large cross sections for dissociation or ionization in collisions with background gas. Since the range of particular interest for molecular dissociation lies below this limit, the electron gun was replaced with one using magnetic confinement of the electron beam. Computer modeling showed that the 250 G magnetic field of this new gun would not prevent collection of the heavy (C-containing) fragments from dissociation of hydrocarbon ions. Measurements of the dissociation cross sections for CD^+ and CH^+ yielding C^+ have commenced. Complementary experiments on the dissociation of these ions yielding D^+ and H^+ have been completed at JILA by collaborators in the group of G. H. Dunn. A Colutron ion source similar to the one used at JILA is being installed on the ORNL electron-ion crossed beams experiment and should produce molecular ions with fewer excited states than those extracted from the ORNL ECR ion source.

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LOW ENERGY STATE-SELECTIVE ELECTRON CAPTURE CROSS SECTIONS USING MERGED BEAMS

W. Wu and C. C. Havener

For the past several years the ion-atom merged-beams apparatus[1] has successfully been used to measure total electron capture cross sections in the energy range between 0.02 and 5000 eV/amu for collisions between multicharged ions and atomic hydrogen (or deuterium). Measurement of the distribution over final states would be a more stringent test of theory which to date has not been routinely performed for collision energies below 100 eV/amu. In order to make state-selective measurements using the merged-beams technique, an energy analyzer has been installed in the merged-beams apparatus which performs translational spectroscopy on the H+ product of the reaction. The analyzer is a simple five-grid retardation analyzer with a resolution of 15-20 volts which is sufficient for most collision systems, since the energy gain (loss) of the reaction in the center-of-mass frame is amplified in the lab due to the frame transformation. As an example, an energy gain spectrum for Si^{4+} + D at 57 eV/amu is shown below where capture to the Si^{3+} (4d) and Si^{3+} (3d) can both be resolved in the cross section differential with respect to the product beam energy. From preliminary analysis, the ratio of the capture of 4s to 3d appears to be significantly less than that predicted from theory.[2] The ratio is a sensitive probe of the role of rotational coupling in the collision. Previous total cross section measurements[3] performed with the merged beams apparatus showed only a slight deviation from the predicted total cross section. Translational spectroscopy is also being applied to endoergic reactions, where the low energy threshold behavior for capture to D(2s) in D^+ + D is being studied. Aided by the fact that the usual D+ background events are filtered out by the energy analyzer, resulting in at least a factor of ten increase in the signal/noise ratio, signal for capture to the nondominant excited state D (2s) has been observed at 300 eV/u. The goal of this investigation will be to determine whether the cross section below 100 eV/amu is characterized by an exponential decrease or a less precipitous decline resulting from the recently proposed decoupling mechanism.[4]

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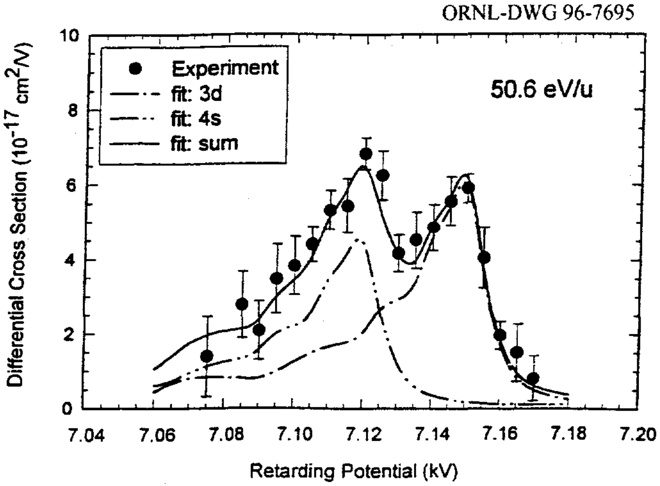

Fig. 4.3. Differential electron capture cross section for the Si^{4+} + D system at 50.6 eV/u.

NEUTRALIZATION AND ANGULAR SCATTERING DURING GRAZING INTERACTIONS OF MULTICHARGED IONS WITH LiF(100)

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While resonant electron capture from metal targets by multicharged ions has been extensively studied for a number of years and can be considered to be reasonably well understood, a similar level of understanding does not yet exist for insulator targets. Such targets have only recently become the focus of intense study.

In order to obtain insight into possible differences between neutralization mechanisms active above metal and insulator surfaces, we have made systematic measurements of image charge acceleration energy gains by multicharged ions approaching a LiF(100) surface, both as function of projectile charge ($3 \leq q \leq 24$) and projectile parallel velocity [$0.1 \leq v(a.u.) \leq 0.56$]. In addition, we have measured velocity dependences of scattered neutral fractions for Na, K, Cs, and Ne projectiles and negative ion fractions for O, F, and B projectiles grazingly incident on LiF(100).

For the alkali and Ne projectiles, a very pronounced incident charge state dependence was found for the scattered neutral fractions. For example, a neutral fraction exceeding 60% was found at the lowest investigated velocities in the case of incident multicharged Na ions, while for incident Na^{1+}, the scattered neutral fraction was measured to be more than an order of magnitude lower. For the Ne incident ions, the charge dependence of the scattered neutral fraction was not as strong, with differences up to a factor of two being observed between the incident 1+ and higher charge state ions at the lowest investigated velocities. At least in the case of the Ne projectiles, this charge state dependence became progressively weaker with increasing velocity, and totally disappeared at velocities above 0.15 a.u. The lower scattered neutral fraction for singly charged incident Na and Ne ions is ascribed to a "blocking" of neutralization due to absence of projectile energy levels resonant with the LiF valence band. For doubly and higher charged projectiles, this bottleneck can be bypassed by double electron capture to quasi-resonant doubly-excited final states on the projectiles. Decay of these projectile states by resonance ionization is blocked in the case of a LiF target due to the forbidden band gap between valence and conduction bands, and must therefore occur by Auger ionization or de-excitation. If the latter process has a sufficiently high transition rate close to the surface, a significant fraction of the scattered doubly excited neutrals will de-excite without change of charge, consistent with the experimental observations.

The measured scattered negative ion fractions all show characteristic kinematic resonance[4] peak shapes with maxima for incident F and O projectiles approaching 80% and 60%, respectively, in good agreement with the measurements of Auth et al.,[5] and for incident B projectiles approaching 3%. Indirect evidence of the correctness of the above explanation for the incident charge dependence in the scattered neutral fractions observed for the alkali ions is provided by the fact that for incident multicharged alkali ions, no production of scattered negative ions is observed, despite the fact that stable negative ions exist for all the alkalis, with positive electron affinities about a factor of two greater than that for B^-. Since these negative ions, however, have ground state neutral cores, and become unstable if the core is (multi)excited, they should not be observed if the precursor neutrals are formed in excited states, as hypothesized above.

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GRAZING ION SURFACE INTERACTION AS PROBE OF SURFACE STATES

Q. Yan, J. Burgdörfer, and F. W. Meyer

Grazing collisions of low energy ions with surfaces provide a sensitive technique for probing surface properties because of the low perpendicular energies (~ few eV) involved in the interaction. The electron density of states at the surface can be studied by resonant charge transfer processes between surface electrons and projectiles. Specifically, the velocity dependence of scattered charge state distributions can give direct information on the electronic structure of 2-D surface bands. The preliminary theory for such an analysis is provided below.

Solution of Schrödinger's equation indicates that surface wavefunctions decay exponentially into the vacuum. In the rest frame of a moving projectile (at $\vec{v}_p$ with respect to the target frame) the surface wavefunction with reduced wavevector k parallel to the surface and energy E can be expressed as a sum over surface reciprocal lattice $\vec{g}$

$$\Psi'_{E,\vec{k}}(\vec{r}', t) = \sum_{\vec{g}} b_{\vec{g}} exp(-\gamma_{\vec{g}} z)\, exp[i(\vec{k} + \vec{g} - \vec{v}_p)\vec{r}'[-i(E - \vec{v}_p(\vec{k} + \vec{g}) + \frac{1}{2}v_p^2)t] \qquad (1)$$

In Eq. (1), only the component with $\vec{g} = 0$ will be considered because components with larger $\vec{g}$ decay faster into the vacuum. Resonant electron transfer occurs when the atomic level of energy E_a equals the energy of the electron at the surface, i.e.

$$E - \vec{v}_p\vec{k} + \frac{1}{2}v_p^2 = E_a \qquad (2)$$

The electron energies of the surface band can be approximated as $E \approx E_b + \frac{1}{2}k^2$ if the Fermi velocity of the surface band is small compared to the reciprocal lattice vector. With this approximation Eq. (2) can be rewritten in the following form: $(\vec{k} - \vec{v}_p)^2 = E_a - E_b \equiv K_a^2$ where E_b is the energy of the bottom of the band. As a result, the fraction of electrons eligible to be resonantly transferred to the projectile atomic level is given by the geometrical overlap between a circle of radius K_a and a disk of radius k_F, the "Fermi velocity" of the surface band, shifted by projectile velocity $\vec{v}_p$ in the momentum plane parallel to the surface. The overlap function is given by the following expression:

$$\Gamma = arccos\left(\frac{E_g + \frac{1}{2}v_p^2}{K_a v_p}\right) / \pi \qquad (3)$$

where E_g is called the "energy gap", i.e., the difference between the target Fermi level and the shifted atomic level in question. The neutral fraction or negative fraction of scattered projectiles is directly proportional to the overlap function. By fitting experimental data as function of parallel velocity, one can obtain E_g, which provides information on the location of the target Fermi level in relation to the relevant projectile level as well as k_F, the "Fermi velocity" of the surface band.

THEORETICAL ATOMIC PHYSICS FOR FUSION

D. R. Schultz, P. S. Krstic, and E. J. Mansky

The Theoretical Atomic Physics for Fusion Program seeks to provide new calculations of atomic collision cross sections of urgent need in fusion energy research. This program is closely coordinated through the Controlled Fusion Atomic Data Center with the Experimental Atomic Physics for Fusion program and with the IAEA International Data Center Network. By these means, and direct contact with the fusion community, particular gaps in the existing database are identified and then addressed.

In particular, contemporary fusion research has focussed a great deal of attention on the issues involved in operating divertors. These components of a fusion reactor serve to cool the hot plasma, extract heat (which in a energy producing reactor would be used to generate electricity), remove the helium ash of fusion, and recycle hydrogen. Because previous theory and experiment sought to describe processes at high collision energies pertaining to the hot central plasma, there exists a substantial need for data regarding the cooler, denser divertor and edge regions. Thus we are seeking to provide calculations of a number of low energy atomic reactions.

For example, we have developed a new method for treating slow collisions involving possibly many electrons.[1] This has been accomplished by generalizing the method of hidden crossings to treat multielectron, multicenter systems, utilizing a molecular Hartree-Fock with single configuration interaction approach. We have demonstrated the success of this method by producing accurate results for ionization in 50 to 1000 eV collisions of H with H. Presently, we are extending this method to more elaborate molecular basis function techniques (e.g., multiconfiguration Hartree-Fock, multiconfiguration interaction) to treat other reactions of interest such as charge transfer in C^+ + H.

Also of recent need is a comprehensive database of elastic scattering differential cross sections and derived transport measures. In the divertor and edge regions of magnetically confined fusion plasmas, it is expected that elastic collisions play a crucial role in the momentum and energy transport. Thus, we have constructed computer codes to mass produce accurate differential cross sections that can be parameterized for ease of use in plasma modeling codes. Extensive tabulations of data including isotopic variants (i.e., involving all combinations of H, D, and T) of proton-hydrogen collisions have been made, and other systems of particular interest such as $Be^{2,1,0+}$ + H have also been addressed. Work is in progress to similarly treat all isotopic variants of proton-H_2 and proton-H_2^+ collisions. For these systems, inelastic (i.e., rovibronic excitation, interchange, and dissociative channels) are also of great interest and are under investigation.

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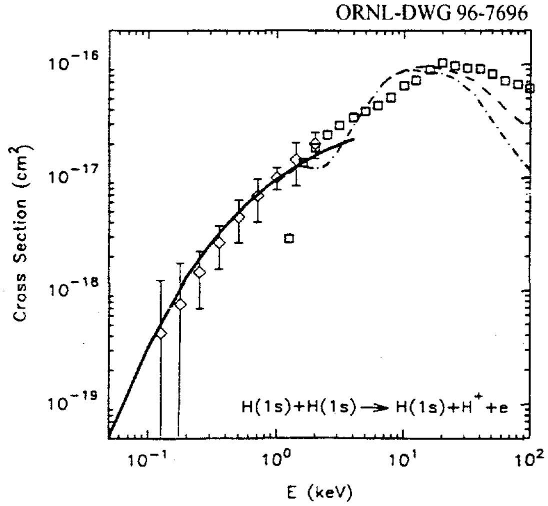

Fig. 4.4. New multielectron, multicenter hidden crossings results for ionization in H + H collisions (solid line) compared with other theoretical and experimental data.

CONTROLLED FUSION ATOMIC DATA CENTER

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The primary mission of the Controlled Fusion Atomic Data Center (CFADC) is to provide critically evaluated atomic collision data to address the most urgent needs of fusion energy research. To this end, ongoing activities include the creation and maintenance of an on-line bibliography of references, participation in an international data center network, and operation of the JET/Strathclyde Atomic Data and Analysis Structure (ADAS).

For example, the CFADC's group of expert consultants has gleaned over the past two years almost three thousand new bibliographic entries which have been added to the on-line bibliography, bringing the total to about 29,000 entries dating from 1978 to present. In addition, an effort which has spanned the last two years to convert archival tapes to readable and parsed tables of entries has just been completed. These entries date from circa 1950 and together with the currently on-line entries total about 72,000. A project to convert the present PC-based bibliographic database to a modern workstation-based system (INGRES) capable of greatly enhanced functionality has almost been completed. A preliminary version of software making the bibliography searchable by any interested user over the widely used World Wide Web has also been set up. The CFADC Website now serves as the primary interface between the data center and the user community, allowing access to the bibliography and other resources such the data stored in the international standard format ALADDIN. Updates to the bibliography still form the basis for the publication "The International Bulletin on Atomic and Molecular Data for Fusion" distributed through the IAEA.

The CFADC Website also provides a convenient medium through which electronic reprints and preprints of our publications of interest to the fusion community can be distributed and provides a wide range of hyperlinks to other resources. We have also set up electronic access to a compilation of data of interest to fusion measured by the Experimental Atomic Physics for Fusion group over the past decade. A project has also been initiated through which the famous CFADC Redbook series of recommended atomic data will be scanned and made available on the Website.

Another very significant resource now available through the data center is ADAS which contains compiled data and modeling software created principally by Hugh Summers at JET and the University of Strathclyde. This package is available at a limited number of laboratories internationally and only through the CFADC in the U.S. It is a sophisticated collisional-radiative modeling suite which allows various derived data to be obtained in support of such modeling and diagnostic tasks as line ratio analysis and the computation of ionization balance and emission. Other cooperative ventures have also been established with laboratories with similar missions. For example, in the aftermath of the closing of the data center at the Joint Institute for Laboratory Astrophysics, we have preserved the considerable database of atomic collision information that was created there and will make it accessible. Further, we are beginning an exchange of data and database technology with the National Institute for Fusion Science in Nagoya, Japan, with the purpose of merging our bibliographic database with their numerically tabulated database. This new suite will be constructed based on our INGRES database and will also have a graphical user interface for displaying and comparing primary numerical data, scaled or semiempirical data and recommended results. Further evolution of that system will allow access through the CFADC Website of the full array of bibliographic and numerical data that we have at our disposal.

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DIAGNOSTICS OF HIGH TEMPERATURE PLASMAS

ALPHA PARTICLE DIAGNOSTIC DEVELOPMENT

R. K. Richards,[1] D. P. Hutchinson,[1] and C. H. Ma

Research towards developing a diagnostic for the measurement of confined high energy alpha particles in ITER has continued. Work in this program includes an investigation of implementing a collective Thomson scattering diagnostic system on two existing tokamak experiments (TFTR and JT-60U) for the purpose of fast ion measurements and the possibility of the measurement of the tritium to deuterium ratio on ITER.[2-4]

Visits were made to both the TFTR and JT-60U sites for the purpose of developing diagnostic systems on these machines for the measurement of fast ion-tails by collective Thomson scattering with a CO_2 laser. The long term goal of this activity is a diagnostic technique capable of measuring the confined high energy alpha particles in ITER. In TFTR the scattering measurement is to be made on the fusion product alpha particles, and on JT-60U the bulk ion tail is to be measured. Although tangential access would be preferred to better simulate a diagnostic for ITER, both of the systems on TFTR and JT-60U would use a vertical port due to the extremely limited space around the center of these machines.

A feasibility study of a diagnostic system capable of measuring the tritium to deuterium ratio in ITER has begun.[5] Such a diagnostic would use the oscillations resonant with the characteristic ion cyclotron harmonic for each ion species in the plasma.

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DEVELOPMENT OF A CO_2 LASER POLARIMETER

C. H. Ma, D. P. Hutchinson,[1] R. K. Richards,[1] and J. Irby[2]

In May 1995, the group successfully carried out the first Faraday rotation measurement in Alcator C-Mod tokamak at MIT. This measurement achieved a high signal-to-noise ratio already at a quite small rotation angle of 0.1°. The electro-optic polarization-modulation technique pioneered by ORNL has been used to achieve the high sensitivity required for this measurement. It is believed that this is the first successful measurement of Faraday rotation in a tokamak by use of a CO_2 laser polarimeter at a wavelength of 10.6 μm. Demonstration of this technique is a significant technical accomplishment for the following reasons: (1) The next generation of fusion machine, such as ITER, presents significantly new and difficult challenges to the measurement of electron density due to the large plasma path length, long pulse length, high density, high plasma current, severely restricted access and the nuclear environment. No diagnostic technique has been demonstrated which is capable of monitoring the density profiles accurately and reliably in such machines. A combination of an interferometer and a Faraday rotation measurement under tangential viewing conditions has been judged as the most feasible diagnostic for future fusion experiments. (2) Faraday rotation measurement of 10.6 μm radiation has never before been successfully demonstrated on a magnetically confined fusion device. (3) The required high sensitivity for this diagnostic has been achieved. The experts in the field have all been highly skeptical that such a measurement was possible. (4) This measurement advances the current state-of-the-art in CO_2 laser polarimeter. The superior performance of the polarimeter indicates not only the possibility of a new generation of plasma diagnostics, but also suggests many important applications of the polarimeter. (5) The diagnostic is nonperturbative of the plasma, and is ideally suited to remote placement and control, which will be essential in the future fusion reactor environment.

The measured data have been analyzed and the results have been documented.[3-5] As a result of this successful endeavor, two research collaboration projects have been initiated. The first project is a collaboration between ORNL and the Japan Atomic Energy Research Institute to develop and implement a CO_2 laser tangential viewing polarimeter on JT-60 tokamak or C-Mod tokamak. The project is currently supported by the U.S.-Japan Fusion Cooperation Program. The second project is a collaboration among ORNL, General Atomics, and the University of California at Los Angeles to develop a CO_2 laser tangential viewing polarimeter for measurement of the electron density profile in ITER. Papers describing this project were published and were presented at appropriate conferences and workshops.[6-8]

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2. Massachusetts Institute of Technology, Plasma Fusion Center, Cambridge, MA.

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ABSTRACTS OF PAPERS PUBLISHED OR SUBMITTED FOR PUBLICATION

CRYSTAL ASSISTED PROCESSES IN ION CHANNELING[1]

S. Datz, H. F. Krause, and C. R. Vane

Channeled ions experience a restoring force from adjacent atomic rows or planes that govern their trajectories and hence limit their interactions to those with valence or conduction electrons. Trajectory information can be gained from emergence patterns and studies of radiative electron capture (REC) can give information on the electron momentum distributions and densities in the channel. With this knowledge, one can study ion-electron collisions in dense media; in particular, dielectronic excitation and recombination. The states of the energetic channeled ions can be influenced by the crystal field and by the wake field that follows them. They can also be perturbed by the periodic electromagnetic force with a frequency depending on their velocity and the periodicity of the lattice. When the frequency of the perturbation ν caused by passing along a given crystal direction with atomic spacing *d* at velocity v reaches a resonance, $\nu_{res} = (v/d)K$, where K = 1, 2, 3, ..., resonant coherent excitation (RCE) can occur to non-degenerate eigenstates of the ion. Ions in these excited states can then be ionized by the channel electrons or, if not ionized, can escape from the crystal and radiate. RCE has been studied in both axial and planar channeling by varying the ion velocity or, in the case of planar channeling, by varying the apparent interatomic spacing by changing the angle with respect to an axis. In both cases, information can be gained concerning the states of channeled ions and the nature of the crystal channel.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res. B* **115**, 363 (1996).

DISSOCIATIVE RECOMBINATION IN H_3^+ AND H_2D^+ (Ref. 1)

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We have measured dissociative recombination (DR) in H_2D^+, and H_3^+. The cross sections were measured over an energy range from 0.001 to 25 eV and are similar except in the region above ~3 eV where "direct" processes dominate. Here the H_2D^+ cross sections are approximately four times smaller than those for H_3^+. The two-body fraction for $H_2D^+ + e \rightarrow H_2 + D$ or HD+H shows much the same behavior as is found for $H_3^+ + e \rightarrow H_2 + H$. At $E_{rel} < 0.1$ eV, the two-body fraction is somewhat higher for H_2D^+, e.g., for H_3^+ at relative energy of 4 eV, the value is 0.65 as against ~0.9 for H_2D^+ at the same energy. An isotope effect in the two-body channel for H_2D^+ is observed giving a product ratio of $HD/H_2 \cong 2.5$ over the entire range. Correcting for the statistical predominance of HD, we get $HD/2H_2 = 1.20 \pm 0.05$.

1. Abstract of published paper: *Dissociative Recombination: Theory, Experiment and Application,* D. Zaifman, editor, World Publishing Singapore (1996), pp. 151-165.
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DOUBLE IONIZATION OF He BY FAST PROTONS AT LARGE ENERGY TRANSFER[1]

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The ratio R(ΔE) of double to single ionization of He by fast proton impact has been measured as a function of energy transfer (ΔE). While R(ΔE) is observed to be nearly independent of proton energy (1–6 MeV) within experimental error, it decreases with increasing energy transfer, from 2% at ΔE = 1 keV to below 1% at ΔE = 10 keV. Further comparisons of these ratios with those obtained from photoionization and Compton scattering are made.

1. Abstract of published paper: *Phys. Rev. Lett.* **76**, 4324 (1996).
2. Oak Ridge National Laboratory Postdoctoral Research Participant.
3. Technion – Israel Institute of Technology, 32000 Haifa, Israel.
4. Hastings College, Hastings, NE.

A SCALING RULE FOR TARGET IONIZATION BY HIGHLY CHARGED IONS AT LOW TO INTERMEDIATE VELOCITIES[1]

W. Wu,[2] E. F. Deveney,[2] S. Datz, D. D. Desai,[3] H. F. Krause, J. M. Sanders,[4] C. R. Vane, C. L. Cocke,[5] and J. P. Giese[5]

Cross sections for ionization of He by highly charged Cl^{q+}, Cu^{q+} and I^{q+} (q = 6–10) impact at velocities from 1.6 to 3.1 a.u. were measured. These results are compared with other experimental and theoretical results available over a wide velocity range. A universal scaling rule for target ionization by nearly bare, highly charged ions at low to intermediate velocities (0.2–3.5 a.u.) is reported.

1. Abstract of published paper: *Phys. Rev. A* **53**, 2367 (1996).
2. Oak Ridge National Laboratory Postdoctoral Research Participant.
3. University of Tennessee, Knoxville, TN.
4. University of South Alabama, Mobile, AL.
5. J. R. Macdonald Laboratory, Kansas State University, Manhattan, KS.

ATOMIC COLLISIONS AT ULTRARELATIVISTIC ENERGIES: 6.4-TeV S AND 33.2-TeV Pb[1]

S. Datz, H. F. Krause, C. R. Vane, P. F. Dittner, E. F. Deveney,[2] H. Knudsen,[3] Per Grafström,[4] R. Schuch,[5] H. Gao,[5] and R. Hutton[6]

We have used beams of 6.4-TeV S ions and 33.2-TeV Pb ions obtained from the CERN-SPS facility to study collision processes of heavy ions at ultrarelativistic energies. Measurements have been made of electron-positron pair production, and capture of an electron produced from the negative continuum onto bound states of the moving ion. Here we report on some aspects of these results. In a new formulation for the theory of electronic stopping power of ions at ultrarelativistic energies, Lindhard and Sørensen (LS) find that nuclear size effects should act to reduce the momentum transfer to electrons and hence the stopping power. Using the 33.2-Pb ions, we measured dE/dx in C, Si, Cu, Sn, and Pb targets. The LS theory was confirmed.

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THE EFFECT OF NUCLEAR SIZE ON THE STOPPING POWER OF ULTRARELATIVISTIC HEAVY IONS[1]

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A new formulation for the theory of electronic stopping power of ions at relativistic energies has been proposed by Lindhard and Sørensen (LS). In it, they find that, at sufficiently high energy, nuclear size effects should act to reduce the momentum transfer to electrons and hence the stopping power. To test this result, we passed beams of 33.2-TeV ^{208}Pb ions ($\gamma = 168$) from the CERN-SPS through targets of C, Si, Cu, Sn, and Pb, and measured energy loss and beam broadening. The LS theory for stopping power is confirmed, but with a slight drift upward from theory for high-Z targets. A drastic decrease in energy straggling (factor of ~14) predicted by LS cannot be deconvoluted from the multiple Coulomb scattering distribution.

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NOVEL APPARATUS AND METHODS FOR PERFORMING REMOTELY CONTROLLED EXPERIMENTS AT CERN[1]

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Recent atomic physics studies involving ultrarelativistic Pb ions required solid target positioners, scintillators, and a sophisticated data acquisition and control system placed in a remote location at the CERN Super Proton Synchrotron near Geneva, Switzerland. The apparatus, installed in a high-radiation zone underground, had to (i) function for months, (ii) automatically respond to failures such as power outages and particle-induced computer upsets, and (iii) communicate with the outside world via a telephone line. The heart of the apparatus developed was an Apple Macintosh-based CAMAC system that answered the telephone and interpreted and executed remote control commands that (i) sensed and set targets, (ii) controlled voltages and discriminator levels for scintillators, (iii) modified data acquisition hardware logic, (iv) reported control information, and (v) automatically synchronized data acquisition to the CERN spill cycle via a modem signal and transmitted experimental data to a remote computer. No problems were experienced using intercontinental telephone connections at 1200 baud. Our successful "virtual laboratory" approach that uses off-the-shelf electronics is generally adaptable to more conventional bench-type experiments.

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ATOMIC COLLISIONS WITH 33-TeV LEAD IONS[1]

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Recent availability of relativistic and ultrarelativistic beams of heavy ions has permitted the first controlled studies of atomic collisions at energies sufficient to measure effects of several new basic phenomena. These include measurements substantiating recently predicted finite nuclear size effects resulting in a reduction in the total electronic energy loss of heavy ions in matter, and measurements of Coulomb collisions in which electrons are excited from the Dirac negative energy continuum. Measurements of total energy loss, free electron-positron pair production, and electron capture from pair production have been recently performed using 33-TeV Pb^{82+} ions from the CERN SPS accelerator in Geneva. Results of these studies are presented, along with comparisons with relevant theory.

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MEASUREMENTS OF POSITRONS FROM PAIR PRODUCTION IN COLLISIONS OF 33-TeV LEAD IONS WITH FIXED TARGETS[1]

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Free positrons from electron-positron pairs produced by 33-TeV Pb^{82+} ions in Coulomb collisions with targets of carbon (polypropylene), aluminum, palladium, and gold have been measured to determine cross sections and momentum distributions. Upper limits have been established for contributions from multiple pair formation. Comparison with similar data taken for 6.4-TeV S^{16+} ions shows that cross sections scale as the product of the squares of the projectile and target nuclear charges. Positron momentum distributions for S^{16+} and Pb^{82+} ions on all targets are observed to be similar, but indicate a tendency for higher energy positron emission for the Pb^{82+} projectiles.

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QUASI-FREE ELECTRON PROCESS IN THE SINGLE IONIZATION OF He BY FAST PROTONS[1]

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Double differential cross sections for the single ionization of He by protons are measured at collision energies of 2, 2.8 and 6 MeV. At energy losses larger than 0.75 keV, single ionization is shown to be dominated by binary encounters between the proton and a quasi-free target electron. The measured scattering angle and energy loss of the protons show a simple two-body kinematic relation. Furthermore, the measured shapes of differential cross sections are in good agreement with calculations of Rutherford scattering from electrons.

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DEPENDENCE OF THE BINARY ENCOUNTER PEAK ENERGY ON THE PROJECTILE CORE[1]

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The energy of the binary encounter peak has been determined for 0.6 MeV/u 0. F, Si, Ti, Cu, and Br ions colliding with H_2 targets. The projectiles all had the same charge q = 7, while the atomic number Z of the projectiles ranged from 8 (almost totally stripped) to 35 (retaining 28 electrons). We observe that the binary encounter peak energy for fixed q increases as Z increases. This trend is opposite of that observed when Z is fixed and the charge q is varied, and it demonstrates that the binary encounter peak energy depends not only on the net projectile charge, but on the projectile core as well. The experimental trend is qualitatively reproduced by an impulse approximation showing that this variation in the binary encounter peak energy may be attributed to the effect that the projectile core potential has on the electron elastic scattering cross section.

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CHANNELING RADIATION FROM LiH and LiD (Ref. 1)

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We have obtained channeling-radiation spectra for both electrons and positrons incident along the major planes of LiH and LiD crystals. Analysis of the data yields two significant results: (1) the thermal-vibration amplitude of LiD is smaller than that of LiH, as one would expect for this isotopic effect, but in contradiction with tabulated values; and (2) a tunneling transition was observed for 54-MeV electron channeling along the (111) planes of both LiH and LiD.

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DISSOCIATIVE RECOMBINATION OF H_2D^+ AND THE COSMIC ABUNDANCE OF DEUTERIUM[1]

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Deuterated molecules in interstellar clouds constitute a unique source of information on three interstellar parameters: the deuterium/hydrogen abundance ratio [D]/[H], the fractional ionization in dense clouds. and the galactic ionizing flux (Dalgarno & Lepp 1984, Millar 1990). The molecular ion H_2D^+

plays a key role in the formation of deuterated molecules. Dissociative recombination with electrons is a major loss channel and a potential source of deuterium atoms.

An ion storage ring has been used to obtain the total recombination rate coefficient, and the probabilities for decay into H+H+D, HD+H, and H_2+D. Using them in a model of the cloud L1529, we derive from observational data on HCO^+ and DCO^+ an upper limit to the fractional ionization of 2×10^{-6}, a [D]/[H] ratio of 1.7×10^{-5} and an atomic D/H ratio of 2.7×10^{-3}.

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DISSOCIATIVE RECOMBINATION AND DISSOCIATIVE EXCITATION OF $^4HeH^+$: ABSOLUTE CROSS SECTIONS AND MECHANISMS[1]

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Absolute cross sections have been determined for the dissociative recombination and dissociative excitation of $^4HeH^+$ for electron energies below 40 eV. The dissociative recombination crosssection is in semi-quantitative agreement with recent theoretical results by Sarpal et al. and Guberman. The calculated resonant structure below a collision energy of 1 eV was not fully reproduced by the experiment. The quantum states of the dissociative recombination products at 0 eV collision energy have been determined; ground-state helium and excited hydrogen atoms (n=2) are dominantly formed, in agreement with recent predictions by Guberman. The dissociative excitation has an onset around 10 eV and follows the shape of the dissociative recombination cross section, illustrating that both processes start with the formation of doubly excited neutral states that lie in the ionization continuum as well as in the dissociation continuum. The dissociative excitation cross section is in quite good agreement with recent calculations by Orel and Kulander.

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DISSOCIATIVE RECOMBINATION OF H_2D^+: CROSS SECTIONS, BRANCHING FRACTIONS, AND ISOTOPES EFFECTS[1]

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H. Danared,[3] A. Källberg,[3] and M. af Ugglas,[3]

We have used the CRYRING heavy-ion storage ring at the Manne Siegbahn Laboratory in Stockholm to store and cool beams of H_2D^+. These beams circulate with energies of MeV per amu and are merged with an electron beam traveling at nearly the same velocity. In this way, relative energies from a fraction of a meV to tens of an eV are achieved. When dissociative recombination (DR) takes place, the neutral fragments exit the ring and strike a detector, enabling the measurement of total DR cross sections. Using this technique, coupled with a "translucent barrier" in which some particles pass directly through holes and others pass through a thin solid and lose part of their energy before striking the detector, we are able to measure the total cross section for DR in H_3^+ and the branching into the three-body (H+H+H) channel and the two-body (H_2+H) channel. Coupling this method with the use of energy absorbers, we are able to measure these quantities for H_2D^+ and the separate two-body channels HD+ H and H_2D. An isotope effect is observed favoring the formation of HD.

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PRODUCT STATE INFORMATION IN DISSOCIATIVE RECOMINATION OF H_2^+ AND HD^+ AND COOLING DYNAMICS IN A STORAGE RING[1]

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We report experiments on dissociative recombination (DR) of HD^+ and H_2^+. Product state information has been obtained over a wide range of electron energies with a position-sensitive detector consisting of a graded absorber in combination with a surface-barrier detector. It is concluded that at low electron energies (<3 eV) hydrogen atoms are fomed preferentially in highly excited states (n>2); at high electron energies (>12 eV) both hydrogen fragments are excited. The dissociative recombination rate of H_2^+ in the energy range of 0 eV to 20 eV has been also measured as a function of storage time. The results of both experiments suggest that an H_2^+ beam is still vibrationally excited after 50 s at our experimental conditions. The dissociative recombination rate of H_2^+ (at 100 K electron temperature) decreases significantly due to interaction with the cooler electrons. This is not observed in a similar experiment with HD^+. Two mechanisms are responsible for the DR rate changes: the high vibrational levels (v->5) have a very high DR-rate. The DR process itself affects their lifetime in the ring. The low vibrational levels may be influenced by superelastic collisions with elections in the cooler on a longer time scale. In constrast to H_2^+, HD^+ cools in a very short time radiatively.

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NON-STATISTICALLY POPULATED AUTOIONIZING LEVELS OF Li-LIKE CARBON: HIDDEN-CROSSINGS[1]

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The intensities of the Auger-electron lines from autoionizing (AI) states of Li-like ($1s2s2\ell$) configurations excited in ion-atom collisions vary as functions of the collision parameters such as, for example, the collision velocity. A statistical population o f the three-electron levels is at best incomplete and underscores the intricate dynamical development of the electronic states. We compare several experimental studies to calculations using 'hidden-crossing' techniques to explore some of the details of these Auger-electron intensity variation phenomena. Our investigations show promising results suggesting that Auger-electron intensity variations can be used to probe collision dynamics.

1. Abstract of published paper: *The Physics Electronic and Atomic Collisions*, L. Dubé, J.A.B. Mitchell, J.W. McConkey, and C. E. Brion, editors, AIP Conf. Proceedings 360, AIP Press, New York (1996), pp. 485-496.
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ABSOLUTE CROSS SECTION FOR DISSOCIATIVE RECOMBINATION OF HD^+ (Ref. 1)

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Absolute cross sections for dissociative recombination of HD^+ were measured in the ion storage CRYRING for incident electron energies in the range 0.01–20 eV. The ions were stored for about 25 s before data taking, which is several orders-of-magnitude longer than their vibrational lifetimes towards spontaneous emission of infrared radiation. A broad resonance in the cross section at 5–12 eV is due to recombination into a manifold of doubly excited states. Multichannel quantum-defect theory was used to calculate the absolute cross section of this resonance. The calculations required inclusion of different mechanisms, such as dissociative autoionization, and many molecular states in order to reproduce the resonance region. Very good agreement of experiment and theory is found, and the results strongly reinforce that vibrationally cold ions were used in the experiment.

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DOUBLE EXCITATION OF HELIUM PRODUCED BY FAST ION IMPACT[1]

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We have measured the electron emission yield for autoionization from the doubly excited states of $2p^2(^1D)$ and $2s2p(^1P)$ of helium produced by C^{q+} (q = 4, 5, 6) ions at a reduced energy of 1.67 MeV/u. The observation angles were between 47.7° and 132.2° with respect to the ion beam direction. The angle and charge-state dependence for these two states are discussed.

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RECOIL-ION CHARGE-STATE-RESOLVED ELECTRON-PRODUCTION CROSS SECTIONS AT 55° FOR 1 MeV/u C^{5+} ON He and Ar (Ref. 1)

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Recoil-ion charge-state-resolved doubly differential cross sections for ejecting electrons at ~55° with respect to the incident beam direction in collisions between 1 MeV/u C^{5+} projectiles and Ar and He targets have been measured. Electrons with kinetic energies between 100 and 1250 eV have been detected. A prominent feature in the electron energy distributions is the binary-encounter peak. Experimental results are compared with binary-encounter electron production cross sections obtained using the impulse approximation and with theoretical predictions from many-body classical trajectory Monte Carlo calculations. An enhancement in the fraction of electrons detected with singly charged He recoil ions and

a corresponding decrease in the fraction detected in coincidence with doubly charged He recoil ions as a function of the electron energy have been observed near the binary-encounter electron energy. This structure has been predicted by recent many-body classical trajectory Monte Carlo calculations.

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CHARGE-STATE DEPENDENCE OF IMAGE-CHARGE ACCELERATION OF CONVOY ELECTRONS IN FAST, GRAZING COLLISIONS OF CARBON IONS WITH SILICON (100) SURFACE[1]

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Electron emission distributions, triply differential in emission energy and angles, are presented for collisions of singly through quadruply charged C ions impinging on a Si(100) surface, with ion energies between 3.6 and 6.0 MeV and grazing angles of incident between 0.1° and 1.0°, respectively. The electron emission spectra measured under these conditions confirm previous reports of a shift of the convoy electron peak toward higher energy due to surface wake or image acceleration. Detailed angular distributions demonstrate a shift of convoy emission toward larger angles with respect to the surface plane, which is further evidence of the acceleration of emitted electrons by the surface wake potential. In addition, we observe the peak energy shift to depend upon the incident ion charge state for the higher projectile velocity (~4.5 a.u.). This dependence may be understood as a consequence of incomplete projectile charge equilibration at the time of convoy electron production. The charge-state dependence is not observed at the lower collision velocity (~3.5 a.u.).

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RESONANCE STATES IN Li^- and B^- (Ref. 1)

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We have observed resonance structures in detached electron spectra arising from fast collisions of Li^- and B^- ions with gas targets. The structures are associated with the autodetaching decay of shape resonance states. Using Shore parametrization, we obtain resonance energies and widths of 50(6) and 64(25) meV, respectively, for the Li^- ($2s2p\ ^3P$) state and 104(8) and 68(25) meV, respectively, for the tentatively identified B^- ($2p^2\ ^1D$) state. Other resonances in B^- remain unidentified.

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PHOTODETACHMENT CROSS SECTIONS[1]

D. J. Pegg[2]

Photodetachment is a fundamental ionization process by which electrons are ejected from negative ions following the absorption of photons. Electron correlation plays a more enhanced role in photodetachment than in photoionization. Experimentally measured photodetachment cross sections serve to guide theory since they constitute sensitive tests of the appropriateness of wavefunctions used in calculations. The status of interacting beam measurements of photodetachment cross sections is reviewed.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res. B* **99**, 140 (1995).
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A SHAPE RESONANCE OBSERVED IN FAST COLLISIONS OF Li^- IONS WITH GAS TARGETS[1]

D. H. Lee,[2] *W. D. Brandon,*[2] *and D. J. Pegg*[3]

A shape resonance state in the Li^- ion, identified as the 2s2p $^3P^{\circ}$ state, has been populated in 100-keV collisions with a He gas target. The resonance was observed via zero-degree electron detachment spectroscopy in which kinematic shifting and doubling were exploited in the detection of the very low energy electrons. The electrons ejected via the resonance gave rise to structures in the electron energy spectra that were disposed about a continuum cusp. These structures corresponded to forward- and backward-directed emission in the projectile frame. Laser photodetached electron spectroscopy was used to accurately calibrate the electron energy scale and to determine the spectrometer resolution function. Preliminary analysis indicates that the measured position and width of the resonant state agree with theoretical values.

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CROSS SECTIONS FOR THE PHOTODETACHMENT OF B^- (Ref. 1)

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Cross sections for photodetaching an electron from a B^- ion have been determined at photon energies of 1.871 and 2.077 eV. A crossed laser-ion-beam apparatus was used to determine the cross sections of B^- relative to those of the reference ion Li^-. The ratios were normalized to previously measured cross sections for the reference ion. The present experiment yields values of $\sigma(B^-) = 24 \pm 4$ Mb (1.871 eV) and 21 ± 3 Mb (2.077 eV).

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ABSOLUTE CROSS SECTIONS FOR ELECTRON-IMPACT SINGLE IONIZATION OF Ne^{q+} (q=2,4-6) ION[1]

M. E. Bannister

Absolute total cross sections for electron-impact single ionization of Ne^{q+} (q=2,4-6) ions have been measured using a crossed-beams technique from below the ground-state ionization threshold to 800 eV with typical total uncertainties near the peak of the cross sections ranging from 9% for Ne^{2+} to 13% for Ne^{6+}. Details of the apparatus and experimental procedures used in this study are presented along with a discussion of the experimental uncertainties. The measured cross sections for all four ions are dominated by direct ionization and are in excellent agreement with the Lotz semiempirical formula. Ionization rate coefficients and fitting parameters calculated from the measured cross sections are also reported.

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1. Abstract of published paper: *Phys. Rev. A* **54**, 1435 (1996).

RESONANCE INTERFERENCE AND ABSOLUTE CROSS SECTIONS IN NEAR-THRESHOLD ELECTRON-IMPACT EXCITATION OF THE $3s^2\ {}^1S \rightarrow 3s3p\ {}^1P$ TRANSITIONS IN Ar^{6+} (Ref. 1)

Y.-S. Chung,[2] N. Djuric,[2] B. Wallbank,[2] G. H. Dunn,[2] M. E. Bannister, and A.C.H. Smith[3]

Strong resonance features were observed in the near-threshold excitation of Ar^{6+}. Absolute total cross sections for electron-impact excitation of the $3s^2\ {}^1S \rightarrow 3s3p\ {}^3P°$ and $3s^2\ {}^1S \rightarrow 3s3p\ {}^1P°$ transitions in Ar^{6+} were measured by using the merged electron-ion beams energy loss technique. The results are compared with the R-matrix close-coupling theory (CCR) and the independent-process isolated-resonance distorted-waves approximation (IPIRDW). Observed disagreement between CCR theory and experiment at the near-threshold peak for the $3s^2\ {}^1S \rightarrow 3s3p\ {}^3P°$ transition is interpreted to be due to very sensitive resonance interference.

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ABSOLUTE CROSS SECTIONS FOR THE ELECTRON-IMPACT SINGLE IONIZATION OF Mo^{4+} AND Mo^{5+} IONS[1]

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Absolute total cross sections for the electron-impact single ionization of Mo^{4+} and Mo^{5+} ions have been measured using a crossed-beams technique from below the ground-state ionization threshold to 500 eV with typical total uncertainties of 9% near the peak of the cross sections. Molybdenum ion production in the source was facilitated by a mini-oven sublimating MoO_3. The measured cross sections are in good agreement with distorted-wave calculations and are dominated by contributions from excitation autoionization. Nonzero cross sections below the threshold for ionization of Mo^{5+} ($4p^6$ 4d) ground-state ions indicate that metastable ions were present in the beam extracted from an electron-cyclotron-resonance ion source. No evidence of metastable ions was found in the case of the Mo^{4+} measurements. Ionization rate coefficients and fitting parameters are presented for the experimental data.

1. Abstract of published paper: *Phys. Rev. A* **52**, 413 (1995).
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THE EVOLVING ROLE OF ATOMIC COLLISIONS IN MAGNETIC FUSION RESEARCH[1]

F. W. Meyer

Atomic physics is playing a prominent role in solving the problem of achieving adequate particle and power exhaust for long pulse/steady state operation of next generation magnetic fusion devices such as ITER. The proposed use of atomic processes to create a "radiating divertor" in which the required power exhaust is achieved will be described and placed into the general context of atomic and plasma-wall interactions occurring in the plasma edge.

1. Abstract of paper to be published in *Comments on Atomic and Molecular Physics.*

TIME SCALES FOR CHARGE EQUILIBRATION OF O^{q+} ($3 \leq q \leq 8$) IONS DURING SURFACE-CHANNELING INTERACTIONS WITH Au(110) (Ref. 1)

L. Folkerts, S. Schippers,[2] D. M. Zehner,[3] and F. W. Meyer

We report on measurements of scattered projectile angular and charge state distributions for 3.75 keV/amu O^{q+} ($3 \leq q \leq 8$) ions surface channeled along the <1$\bar{1}$0> direction of a Au(110) single crystal target. Projectile trajectory calculations indicate that the projectiles spend less than 30 fs within 2 Å of the topmost Au surface layer. Nevertheless, almost complete charge equilibration is observed in the scattered projectile charge state distributions. It is concluded that, *already at the target interface,* strong screening effects are present which make possible direct capture to the projectile *L* and *M* shells in relatively large impact parameter collisions.

1. Abstract of published paper: *Phys. Rev. Lett.* **74**, 2204 (1995).
2. Kernfysisch Versneller Instituut, Groningen, The Netherlands.
3. Solid State Division, ORNL.

FAST NEUTRALIZATION OF HIGHLY CHARGED IONS IN GRAZING INCIDENCE COLLISIONS WITH SURFACES[1]

J. Burgdörfer, C. Reinhold, and F. Meyer

We present first results of simulations for the neutralization and relaxation of multiply charged O^{q+} ions in grazing incidence collisions with a gold surface. The simulation treats the direct quasi-resonant charge transfer into the L shell of the projectile within the over-the-barrier model. The speed of neutralization is significantly enhanced by the upward shift of energy levels at the surface due to dynamical screening. We find complete relaxation, neutralization, and negative ion formations within the available interaction time of a few times 10^{-14} s in agreement with experiment.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res. B* **98**, 415 (1995).

ANGULAR AND CHARGE STATE DISTRIBUTIONS OF HIGHLY CHARGED IONS SCATTERED DURING LOW ENERGY SURFACE-CHANNELING INTERACTIONS WITH Au(110) (Ref. 1)

F. W. Meyer, L. Folkerts, and S. Schippers[2]

We have measured scattered projectile angular and charge state distributions for 3.75 keV/amu O^{q+} ($3 \leq q \leq 8$) and 1.2 keV/amu Ar^{q+} ($3 \leq q \leq 14$) ions grazingly incident along the [110] and [100] directions of a Au(110) single crystal target. Scattered projectile angular distributions characteristic of surface channeling are observed. For both incident species, the dominant scattered charge fraction is neutral, which varies only by a few percent as a function of incident charge state. Significant O^- formation is observed, which manifests a distinct velocity threshold. For incident Ar projectiles with open L-shell, the positive scattered charge fractions, while always less than about 10%, increase linearly with increasing number of initial L-shell vacancies.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res. B* **100**, 366 (1995).
2. University of Osnabrück, Osnabrück, Germany.

PROJECTILE IMAGE ACCELERATION, NEUTRALIZATION AND ELECTRON EMISSION DURING GRAZING INTERACTIONS OF MULTICHARGED IONS WITH Au(110) (Ref. 1)

F. W. Meyer, L. Folkerts, H. O. Folkerts,[2] *and S. Schippers*[3]

Recent Oak Ridge work is summarized on projectile energy gain by image charge acceleration, scattered ion charge distributions, and K-Auger electron emission during low energy grazing interactions of highly charged Pb, I, O and Ar ions with a Au(110) surface.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res. B* **98**, 441 (1995).
2. Kernfysisch Versneller Instituut, Groningen, The Netherlands.
3. Osnabrück University, Osnabrück, Germany.

IMAGE ACCELERATION OF HIGHLY CHARGED IONS BY METAL SURFACES[1]

C. Lemell,[2] *H. P. Winter,*[2] *F. Aumayr,*[2] *J. Burgdörfer, and F. Meyer*

We present classical simulations for the energy gain, ΔE, due to the image acceleration of very highly charged ions ($Q \gg 10$) by metal surfaces. We show that for large Q the simulated values ΔE, based on the classical over-barrier model, fall below the "staircase" model but still exceed the lower bound for classically allowed transitions. The results are in reasonable agreement with recent experimental data. Effects of the nonzero velocity of the projectile parallel to the surface appear to be insignificant for the energy gain.

1. Abstract of published paper: *Phys. Rev. A* **53**, 880 (1996).
2. Institut für Allgemeine Physik, Vienna, Austria.

PROJECTILE VELOCITY AND TARGET TEMPERATURE DEPENDENCE OF CHARGE-STATE DISTRIBUTIONS OF MULTICHARGED IONS SCATTERED DURING GRAZING INTERACTIONS WITH A Au(110) SURFACE[1]

Q. Yan, D. M. Zehner,[2] F. W. Meyer, and S. Schippers[3]

We have made systematic measurements of scattered projectile charge-state distributions for multicharged He, N, Ne, Na, and Ar ions grazingly incident on a Au(110) single-crystal target. For projectiles whose neutral binding energies lie below the valence band (N, Ar, He, and Ne), observed 1+ charge fractions were small at low velocities and steeply increased above well-defined threshold velocities. However, for Na projectiles with neutral binding energy above the Fermi level, a large (about 84%) 1+ charge fraction was found. The velocity dependence of the Na neutral fraction shows a "kinematic resonance" due to the virtual population of electronic states above the Fermi level in the projectile rest frame. The measured sample temperature dependence of the scattered 1+ charge fraction for Ne^{9+} projectiles incident along the [110] surface channeling direction reveals a significant decrease in projectile neutralization once the (2×1)-(1×1) phase transition temperature of the Au(110) surface at 650 K has been reached.

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1. Abstract of published paper: *Phys. Rev. A* **54**, 641 (1996).
2. Solid State Division, ORNL.
3. Kernfysisch Versneller Institute, Groningen, The Netherlands.

PROJECTILE NEUTRALIZATION DURING GRAZING INTERACTIONS OF MULTICHARGED IONS WITH LiF(100) (Ref. 1)

Q. Yan and F. W. Meyer

Measurements are reported of scattered neutral fractions for Na, K, and Cs multicharged ions, and of scattered negative ion fractions for incident O, F, and B projectiles grazingly incident on Li(100) as function of projectile velocity. The possibility of the involvement in the projectile neutralization of occupied surface states within the band gap of the alkali halide target is considered. A model treatment of the projectile charge fraction velocity dependence is utilized to demonstrate that an occupied surface band having work function and Fermi energy of 3.8 eV and 0.8 eV, respectively, can reproduce the velocity dependences of all the above experimental data, as well as that of the image charge acceleration of Ne^{6+} grazingly incident on LiF(100) in the range 0.1-0.52 a.u.

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1. Abstract of paper to be published by Trans Tech Pub. Ltd. (Switzerland).

ON THE NEUTRALIZATION OF SINGLY AND MULTICHARGED PROJECTILES DURING GRAZING INTERACTIONS WITH LiF(100) (Ref. 1)

F. W. Meyer, Q. Yan, P. Zeijlmans van Emmichoven,[2] I. G. Hughes,[3] and G. Spierings[2]

Measurements are reported of scattered neutral fractions for Na, K, Cs, and Ne singly and multicharged ions, and of scattered negative ion fractions for incident O, F, and B projectiles grazingly incident on LiF(100) as function of projectile velocity. In the case of the Na and Ne incident ions, significant dependence of the scattered neutral fractions on incident charge state is found, which is most pronounced at the lowest investigated velocities. Possible reasons for the observed initial charge state dependence are considered. In addition, results are reported for the target azimuthal dependence of the final neutral fraction observed for grazingly incident 35 keV Cs^{7+} ions.

1. Abstract of invited paper to be published in *Nuclear Instruments and Methods in Physics Research B*.
2. Utrecht University, Utrecht, The Netherlands.
3. The Queen's University of Belfast, United Kingdom.

MERGED BEAMS WITH MULTICHARGED IONS[1]

C. C. Havener

The feasibility of using a merged-beams technique to measure interactions at low collision energies was first successfully demonstrated in 1966 and involved measurements of symmetric charge exchange for 5 eV/amu collisions of Ar^+ + Ar. Soon after, the technique was expanded to study collisions with a variety of atomic ions and neutrals, molecular ions, and electrons. Merged-beams measurements were found to be technically difficult and were generally limited to ions with low charge states (where beams of sufficient intensity existed) and to collision processes characterized by large cross sections. The recent advent of advanced ion sources, e.g., the ECR source, has allowed the merged-beams technique to be further expanded to study collisions with multicharged ions. At ORNL an ion-atom merged-beams technique has recently been used to study electron capture with multicharged ions to near-thermal collisions energies. Details of the apparatus will be used to illustrate the merged-beams technique. Recent electron capture cross section measurements will be presented to illustrate the importance of the merged-beams technique in the study of low energy electron capture.

1. Abstract of paper to be published in *Accelerator-Based Atomic Physics Techniques and Applications*, ed. S. Shafroth and J. Austin, AIP.

LOW-ENERGY ELECTRON CAPTURE BY C^{3+} FROM HYDROGEN USING MERGED BEAMS[1]

C. C. Havener, A. Müller,[2] P. A. Zeijlmans van Emmichoven,[3] and R. A. Phaneuf[4]

Measurements of absolute total cross sections for electron capture by C^{3+} in collisions with ground-state hydrogen and deuterium are reported in the energy range 0.3-3000 eV/u. In general, good agreement is obtained with published experimental measurements at the lower (10-110 eV/u) and higher (>1 keV/u) collision energies. However, the improved accuracy and the large energy range of these measurements made possible by the merged-beams technique indicate an energy dependence different than was suggested by interpolating previous published and unpublished measurements and by a theoretical calculation that attempted to reconcile the previous low- and high-energy total-capture cross-section data. The present measurements above 100 eV/u show excellent agreement with a more recent 22-state molecular-orbital calculation that predicts slight structure in the cross section at collision energies between 1000 and 2000 eV/u. Below 100 eV/u, the present measurements, which were performed with deuterium, deviate from an energy dependence suggested by earlier hydrogen measurements and by fully quantal calculations.

1. Abstract of published paper: *Phys. Rev. A* **51**, 2982 (1995).
2. Institut für Strahlenphysik der Universität Stuttgart, Stuttgart, Germany.
3. Utrecht University, Utrecht, The Netherlands.
4. University of Nevada, Reno, NV.

COLLISIONS OF HIGHLY CHARGED IONS WITH ELECTRONS, ATOMS AND SURFACES[1]

C. C. Havener, M. E. Bannister, L. Folkerts, J. W. Hale, M. Pieksma, J. Shinpaugh,[2] and F. W. Meyer

At the Oak Ridge Multicharged Ion Source Facility, an experiment atomic collisions physics program is centered around a recently upgraded Electron Cyclotron Resonance (ECR) multicharged ion source. The 10 GHZ CAPRICE source has been in operation since October 22, 1992, and has provided more intense, higher charge ion beams than our previous ECR ion source. Intense metallic beams have recently become available with the installation of a metallic oven on the source. In addition to measurements of electron-impact excitation, carried out in collaboration with the Joint Institute for Laboratory Astrophysics (JILA), experiments are presently on-line to study electron-impact ionization, low-energy ion-atom collisions, and ion-surface interactions. A brief summary of our various activities with an emphasis on the new capabilities is presented.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res. B* **99**, 213 (1995).
2. East Carolina University, Greenville, NC.

ELECTRON-CAPTURE CROSS SECTION AT NEAR-THERMAL COLLISION ENERGIES FOR Si^{4+} + D (Ref. 1)

M. Pieksma, M. Gargaud,[2] R. McCarroll,[3] and C. C. Havener

Using a merged-beams technique, absolute total electron-capture cross sections have been measured in the thermal energy regime for collisions of Si^{4+} ions with neutral D atoms. State-of-the-art molecular-orbital coupled-channel calculations for the Si^{4+} + H(D) systems are compared to the measurements on an absolute scale. Both the existence of a surprisingly large kinematic isotope effect and an observed sharp low-energy increase of the cross section are attributed to trajectory effects due to an attractive ion-induced dipole.

1. Abstract of published paper: *Phys. Rev. A* **54**, R13 (1996).
2. Observatoire de l'Universite de Bordeaux I, Floirac, France.
3. Laboratoire de Dynamique Moleculaire et Atomique, University Pierre et Marie Curie, Paris Cedex, France.

LOW-ENERGY ELECTRON CAPTURE BY N^{4+} IONS FROM H ATOMS: EXPERIMENTAL STUDY USING MERGED BEAMS AND THEORETICAL ANALYSIS BY MOLECULAR REPRESENTATION[1]

L. Folkerts, M. A. Haque,[2] C. C. Havener, N. Shimakura,[3] and M. Kimura[3]

Measurements and theoretical analyses of total electron-capture cross sections for collisions of N^{4+} with ground-state hydrogen (deuterium) are reported in the energy range 1-300 eV/u. The present measurements have reduced relative uncertainty compared to previous absolute measurements at Oak Ridge National Laboratory [Huq et al., Phys. Rev. A **40**, 1811 (1989)] and are used for detailed comparison with more recent coupled-channel molecular-orbital calculations [Shimakura et al., Phys. Rev. A **45**, 267 (1992); Zygelman et al., ibid. **46**, 3846 (1992)]. The most striking difference between the calculations was the increasing trend in the cross section for collision energies below 4 eV/u, as estimated by Zygelman et al. using only singlet states of the quasimolecule and the decreasing trend predicted by Shimakura et al. using both singlet and triplet states. The latter decreasing trend is consistent with the previous measurements. At 0.5 eV/u, the predicted singlet cross sections differ nearly by a factor of 2. Possible origins for this difference are explored. Strong structure is predicted in the cross section of Zygelman et al. and, to a lesser extent, in that of Shimakura et al.; however, the phase of the structure is different in the two theories. Structures observed in the measurement at the higher collision energies are not in complete harmony with either prediction.

1. Abstract of published paper: *Phys. Rev. A* **51**, 3685 (1995).
2. Alcorn State University, Lorman, MS.
3. Argonne National Laboratory, Argonne, IL, and Rice University, Houston, TX.

LOW ENERGY ELECTRON CAPTURE BY N^{2+} FROM ATOMIC HYDROGEN USING MERGED BEAMS[1]

M. Pieksma, M. E. Bannister, W. Wu, and C. C. Havener

Using the merged-beams technique, independently absolute total electron capture cross sections have been measured for the N^{2+} + H (or D) system in the energy range 0.1-4500 eV/amu. For collision energies less than 200 eV/amu the new data are in reasonable accord with recent fully quantal calculations of Herrero et al., except that no evidence exists for the predicted peak in the cross section at 0.25 eV/amu. The existence of additional structure between 10 and 100 eV/amu predicted by Bienstock eta l. is not seen. Above 2000 eV/amu excellent agreement is found with other measurements using a hydrogen furnace. However, between 200 and 2000 eV/amu the present results are some 30% below the previously published experimental and theoretical cross sections, and a local maximum is found near 200 eV/amu rather than 350 eV/amu. A possible explanation for this discrepancy is suggested.

1. Abstract of paper submitted to *Physical Review A.*

NEW METHOD FOR TREATING SLOW MULTIELECTRON, MULTICENTER ATOMIC COLLISIONS[1]

P. S. Krstic, G. Bent,[2] and D. R. Schultz

The method of hidden crossings is generalized to treat multielectron systems utilizing molecular Hartree-Fock and configuration interaction methods, extended into the plane of complex internuclear distance. Diabatic promotion of low lying states to the continuum in a two-electron, two-center system via a series of localized transitions is shown for the first time. Excellent agreement with experiments is found regarding single ionization in 50 eV to 1 keV H + H collisions.

1. Abstract of published paper: *Phys. Rev. Lett.* **77**, 2428 (1996).
2. University of Connecticut, Storrs, CT.

ELECTRON COLLISIONS WITH ATOMS AND ATOMIC IONS[1]

D. R. Schultz

Excitation and ionization of atoms and ions by electron-impact continues to be an area of very active investigation. Access to the most up-to-date data produced may be obtained either through new works which provide collections, evaluations, and recommendations, or through the original works which can be located through bibliographic databases and articles.

1. Abstract of paper to be published in *IAU Transactions*, Vol. XXIIIA.

INELASTIC PROCESSES IN 0.1-1000 keV/u COLLISIONS OF Ne^{q+} (q=7-10) IONS WITH ATOMIC HYDROGEN[1]

D. R. Schultz and P. S. Krstic

Owing to the potential use of neon as an intentionally introduced radiating impurity in fusion reactor divertors, we present here cross sections for (*i*) ionization, (*ii*) state-selective excitation, and (*iii*) state-selective charge transfer in 0.1-1000 keV/u collisions of Ne^{q+} (q=7-10) with H. The cross sections may be used in modeling and diagnosing the distribution and state of these ions as well as other parameters of the core, edge, and divertor regions of the plasma. We have utilized the theory of hidden crossings in the low energy portion of the energy range considered and the classical trajectory Monte Carlo method throughout the high energy portion.

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1. Abstract of paper to be published in *Atomic and Plasma-Material Interaction Data for Fusion* (supplement to *Nuclear Fusion*), 1996.

ELASTIC PROCESSES IN SLOW COLLISIONS OF Be AND Be IONS WITH HYDROGEN[1]

P. Krstic, D. R. Schultz, and G. Bent[2]

Because of their present relevance to divertor modeling of fusion reactors, differential and total elastic cross sections have been calculated for collisions of Be, Be^{+} and Be^{2+} in the ground state with atomic hydrogen. The collision energy was varied over more than four orders of magnitude, from 0.01 eV up to 500 eV. The differential cross sections are shown for the full range of scattering angles, at four representative values of energy. The total elastic cross section and its plasma transport relevant moments (momentum transfer, viscosity) are presented as functions of the energy.

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1. Abstract of published paper: *Physica Scripta* **T62**, 21 (1996).
2. University of Connecticut, Storrs, CT.

INELASTIC PROCESSES IN 1-1000 keV/u COLLISIONS OF Be^{q+} (q=2-4) IONS WITH ATOMIC AND MOLECULAR HYDROGEN[1]

D. R. Schultz, P. S. Krstic, and C. O. Reinhold

Owing to the use of beryllium in fusion reactors and the consequent need to model and diagnose plasmas containing this species of impurity, cross sections are presented here for inelastic collisions of 1-1000 keV/u Be^{q+} (q=2-4) with H and H_2. In particular, the classical trajectory Monte Carlo technique is used to compute total cross sections for (*i*) ionization, (*ii*) state-selective excitation, and (*iii*) state-selective charge transfer.

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1. Abstract of published paper: *Physica Scripta* **T62**, 69 (1996).

ON-LINE ATOMIC DATA ACCESS[1]

D. R. Schultz and J. K. Nash[2]

The need for atomic data is one which continues to expand in a wide variety of applications including fusion energy, astrophysics, laser-produced plasma research, and plasma processing. Modern computer database and communications technology enables this data to be placed on-line and obtained by users over the INTERNET. Presented here is a summary of the observations and conclusions regarding such on-line atomic data access derived from a forum held at the *Tenth APS Topical Conference on Atomic Processes in Plasmas.*

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1. Abstract of paper published in Proceedings of Tenth Topical Conference on Atomic Processes in Plasmas, ed. by A. L. Osterheld and W. H. Goldstein (AIP Conference Proceedings 381, AIP Press, 1996), p. 197.
2. Lawrence Livermore National Laboratory, Livermore, CA.

ATOMIC AND MOLECULAR DATA NEEDS FOR FUSION[1]

D. R. Schultz

Atomic and molecular processes in plasmas play a crucial role in the development of net energy producing magnetic fusion devices. In light of this fact, presented here is a survey of the broad needs of fusion energy research and a review of the status of the existing database. Emphasis is placed on the relatively new needs for data as novel materials are evaluated for use in the next devices, and as components such as the divertor take on more significance for demonstration and practical reactors. Also, examples are given of recent or ongoing data evaluation efforts, the role of national and international data centers is discussed, and some summarizing comments are given.

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1. Abstract of paper published in Proceedings of Ninth APS Topical Conference, Atomic Processes in Plasmas, ed. by W. L. Rowan (AIP Press, 1996), p. 3.

MICROWAVE SCATTERING DIAGNOSTIC ON THE ADVANCED TOROIDAL FACILITY TORSATRON[1]

M. G. Shats,[2] K. M. Likin,[3] J. B. Wilgen,[4] J. H. Harris,[4] K. A. Sarksyan,[3] L. R. Baylor,[4] J. D. Bell,[4] T. S. Bigelow,[4] J. L. Dunlap,[4] R. C. Goldfinger,[4] and C. H. Ma

A 2 mm scattering diagnostic used to study density fluctuations of the electron cyclotron resonance heated plasma in the Advanced Toroidal Facility is described. A four-channel flexible antenna design was chosen to monitor fluctuations within the wave number range of $3<k_\perp<20$ cm^{-1} and to locate the scattering volume anywhere in the stellarator minor cross section. Special attention was paid to the system calibration and to the normalization of the *k* spectra. Analysis of the diagnostic noise showed that the main source of spurious signal was a scattering from high-level edge turbulence driven by the second-harmonic radiation from the gyrotron used for plasma heating. This spurious signal was suppressed using waveguide filters and rearrangement of the microwave circuit elements. Evidence in support of direct scattering from a well-defined plasma volume was found. Good correlation of the scattered waves' intensity with the density scale length was observed. Use of a dual-homodyne circuit configuration made it possible to determine that the plasma density fluctuations were propagating in the electron diamagnetic direction.

1. Abstract of published paper: *Rev. Sci. Instrum.* **66**, 1221 (1995).
2. Australian National University, Canberra, Australia.
3. General Physics Institute, Moscow, Russia.
4. Fusion Energy Division, ORNL.

DENSITY FLUCTUATIONS IN THE ADVANCED TOROIDAL FACILITY (ATF) TORSATRON[1]

M. G. Shats,[2] J. H. Harris,[3] J. B. Wilgen,[3] L. R. Baylor,[3] J. D Bell,[3] C. H. Ma, M. Murakami,[3] T. S. Bigelow,[3] G. L. Bell,[3] R. J. Colchin,[3] R. A. Dory,[3] J. L. Dunlap,[3] G. R. Dyer,[3] A. C. England,[3] G. R. Hanson,[3] D. P. Hutchinson,[4] R. C. Isler,[3] T. C. Jernigan,[3] R. A. Langley,[3] D. K. Lee,[3] J. F. Lyon,[3] A. L. Qualls,[3] D. A. Rasmussen,[3] R. K. Richards,[4] M. J. Saltmarsh,[3] J. E. Simpkins,[3] K. L. Vander Sluis, K. M. Likin,[5] K. A. Sarksyan,[5] S. C. Aceto,[6] and J. J. Zielinski[7]

Density fluctuations in low-collisionality, low-beta ($\beta \sim 0.1\%$), currentless plasmas produced with electron cyclotron heating (ECH) in the Advanced Toroidal Facility (ATF) torsatron have been studied using a 2-mm microwave scattering diagnostic. Pulsed gas puffing is used to produce transient steepening of the density profile from its typically flat shape; this leads to growth in the density fluctuations when the temperature and density gradients both point in the same direction in the confinement region. The wave number spectra of the fluctuations that appear during this perturbation have a maximum at higher $k_\perp \rho_s$ (~1) than is typically seen in tokamaks. The in-out asymmetry of the fluctuations along the major radius correlates with the distribution of confined trapped particles expected for the ATF magnetic field geometry. During the perturbation, the relative level of the density fluctuations in the confinement region (integrated over normalized minor radii ρ from 0.5 to 0.85) increases from $\tilde{n}/n \sim 1\%$ when the density profile is flat to $\tilde{n}/n \sim 3\%$ when the density profile is steepened. These observations are in qualitative agreement with theoretical expectations for helical dissipative trapped-electron modes (DTEMs), which are drift-wave instabilities associated with particle trapping in the helical stellarator field.

1. Abstract of published paper: *Trans. Fusion Technol.* **27**, 481 (1995).
2. Australian National University, Canberra, Australia.
3. Fusion Energy Division, ORNL.
4. Instrumentation and Controls Division, ORNL.
5. General Physics Institute, Moscow, Russian Federation.
6. Interscience, Inc., Troy, NY.
7. Rensselaer Polytechnic Institute, Troy, NY.

DESIGN OF A CO_2-LASER THOMSON SCATTERING ION-TAIL DIAGNOSTIC FOR ALCATOR C-MOD[1]

R. K. Richards,[2] D. P. Hutchinson,[2] and C. H. Ma

A CO_2-laser Thomson scattering diagnostic has been designed for the measurement of the ICRH-produced ion tail on Alcator C-Mod. The plasma parameters and port access require that the detection of scattered radiation be made at small angles, typically 1° or less. The receiver system consists of five heterodyne detectors and the source laser produces an energy of 10 J per pulse with a 1-5 μs pulse length. The scattering system is currently being installed on the Alcator C-Mod experiment. Details of the diagnostic, calculations of the expected measurements, and application of the diagnostic for ITER are presented.

1. Abstract of published paper: *Rev. Sci. Instrum.* **66**, 497 (1995).
2. Instrumentation and Controls Division, ORNL.

DRIFT-WAVE-LIKE DENSITY FLUCTUATIONS IN THE ADVANCED TOROIDAL FACILITY (ATF) TORSATRON[1]

M. G. Shats,[2] *J. H. Harris,*[3] *K. M. Likin,*[4] *J. B. Wilgen,*[3] *L. R. Baylor,*[3] *J. D Bell,*[5] *C. H. Ma, M. Murakami,*[3] *K. A. Sarksyan,*[4] *S. C. Aceto,*[6] *T. S. Bigelow,*[3] *G. L. Bell,*[3] *R. J. Colchin,*[3] *R. A. Dory,*[3] *J. L. Dunlap,*[3] *G. R. Dyer,*[3] *A. C. England,*[3] *R. C. Goldfinger,*[5] *G. R. Hanson,*[3] *D. P. Hutchinson,*[7] *R. C. Isler,*[3] *T. C. Jernigan,*[3] *R. A. Langley,*[3] *D. K. Lee,*[5] *J. F. Lyon,*[3] *A. L. Qualls,*[3] *D. A. Rasmussen,*[3] *R. K. Richards,*[7] *M. J. Saltmarsh,*[3] *J. E. Simpkins,*[3] *K. L. Vander Sluis, and J. J. Zielinski*[8]

Density fluctuations in low-collisionality, low-beta (β~0.1%), currentless plasmas produced with electron cyclotron heating (ECH) in the Advanced Toroidal Facility (ATF) torsatron [Fusion Technol. **10**, 179 (1986)] have been studied using a 2 mm microwave scattering diagnostic. Pulsed gas puffing is used to produce transient steepening of the density profile from its typically flat shape; this leads to growth in the density fluctuations when the temperature and density gradients both point in the same direction in the confinement region. The wave number spectra of the fluctuations that appear during this perturbation have a maximum at higher $k_\perp\rho_s$ (~1) than is typically seen in tokamaks. The in-out asymmetry of the fluctuations along the major radius correlates with the distribution of confined trapped particles expected for the ATF magnetic field geometry. During the perturbation, the relative level of the density fluctuations in the confinement region (integrated over normalized minor radii ρ from 0.5 to 0.85) increases from $\tilde{n}/n \sim 1\%$ when the density profile is flat to $\tilde{n}/n \sim 3\%$ when the density profile is steepened. These observations are in qualitative agreement with theoretical expectations for helical dissipative trapped-electron modes (DTEMs), which are drift-wave instabilities associated with particle trapping in the helical stellarator field; they suggest that trapped-electron instabilities may play a role in constraining the shape of the density profile in ATF, but have little effect on global energy confinement.

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1. Abstract of published paper: *Phys. Plasmas* **2**, 398 (1995).
2. Australian National University, Canberra, Australia.
3. Fusion Energy Division, ORNL.
4. General Physics Institute, Moscow, Russian Federation.
5. Computing and Telecommunications Division, Y-12.
6. Interscience, Inc., Troy, NY.
7. Instrumentation and Controls Division, ORNL.
8. Rensselaer Polytechnic Institute, Troy, NY.

CO_2 LASER POLARIMETER FOR MEASUREMENT OF PLASMA CURRENT PROFILE IN ALCATOR C-MOD[1]

C. H. Ma, D. P. Hutchinson,[2] *R. K. Richards,*[2] *J. Irby,*[3] *and T. Luke*[3]

A multichannel infrared polarimeter system for measurement of the plasma current profile in Alcator C-Mod has been designed, constructed, and tested. The system utilizes a cw CO_2 laser at a wavelength of 10.6 μm. An electro-optic polarization-modulation technique has been used to achieve the high sensitivity required for the measurement. The recent results of the measurements as well as the feasibility of its application on international thermonuclear experimental reactor are presented.

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1. Abstract of published paper: *Rev. Sci. Instrum.* **66**, 376 (1995).
2. Instrumentation and Controls Division, ORNL.
3. Massachusetts Institute of Technology, Plasma Fusion Center, Cambridge, MA.

APPLICATION OF INTERFEROMETRY AND FARADAY ROTATION TECHNIQUES FOR DENSITY MEASUREMENTS ON ITER[1]

R. T. Snider,[2] T. N. Carlstrom,[2] C. H. Ma, and W. A. Peebles[3]

There is a need for real time, reliable density measurement for tokamak plasma density control, compatible with the restricted access and radiation environment on ITER. Line average density measurements using microwave or laser interferometry techniques have proven to be robust and reliable for density control on contemporary tokamaks. In ITER, the large path length, high density and high density gradients limit the wavelength of a probing beam to shorter than about 50 μm due to refraction effects. In this paper we consider the design of short wavelength vibration compensated interferometers and Faraday rotation techniques for density measurements on ITER. These techniques allow operation of the diagnostics without a prohibitively large vibration isolated structure and permit the optics to be mounted directly on the radial port plugs on ITER. A beam path designed for 10.6 μm (CO_2 laser) with a tangential path through the plasma allows both an interferometer and a Faraday rotation measurement of the line average density with good density resolution while avoiding refraction problems. Plasma effects on the probing beams and design tradeoffs will be discussed along with radiation and long pulse issues. A proposed layout of the diagnostic for ITER will be presented.

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1. Abstract of published paper: pp. 225-33 in *Diagnostics for Experimental Thermonuclear Fusion Reactors*, ed. P. E. Stott et al., Plenum Press, New York, 1996.
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INFRARED LASER DIAGNOSTICS FOR ITER[1]

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Two infrared laser-based diagnostics are under development at the Oak Ridge National Laboratory (ORNL) for measurements on burning plasmas such as ITER. Our primary effort is the development of a CO_2 laser Thomson scattering diagnostic for the measurement of the velocity distribution of confined fusion-product alpha particles. This diagnostic utilizes small-angle collective scattering of infrared light from the electron cloud surrounding the alpha particles. Key components of the system include a high-power, single-mode CO_2 pulsed laser, an efficient optics system for beam transport and a multichannel low-noise infrared heterodyne receiver. A successful proof-of-principle experiment has been performed on the Advanced Toroidal Facility (ATF) stellarator at ORNL utilizing scattering from electron plasma frequency satellites. The diagnostic system is currently being installed on Alcator C-Mod at MIT for measurements of the fast ion tail produced by ICRH heating. A second diagnostic under development at ORNL is an infrared polarimeter for Faraday rotation measurements in future fusion experiments. A preliminary feasibility study of a CO_2 laser tangential viewing polarimeter for measuring electron density profiles in ITER has been completed. For ITER plasma parameters and a polarimeter wavelength of 10.6 μm, a Faraday rotation of up to 26° is predicted. An electro-optic polarization modulation technique has been developed at ORNL. Laboratory tests of this polarimeter demonstrated a sensitivity of $\leq$0.01°. Because of the similarity in the expected Faraday rotation in ITER and Alcator C-Mod, a collaboration between ORNL and MIT Plasma Fusion Center has been undertaken to test this polarimeter system on Alcator C-Mod. A 10.6 μm polarimeter for this measurement has been constructed and integrated into the existing C-Mod multichannel two-color interferometer. With present experimental parameters for C-Mod, the predicted Faraday rotation was on the order of 0.1°. Significant output signals were observed during preliminary tests. Further experiment and detailed analyses are under way.

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1. Abstract of published paper: pp. 245-48 in *Diagnostics for Experimental Thermonuclear Fusion Reactors*, ed. P. E. Stott et al., Plenum Press, New York, 1996.
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5. THEORETICAL AND COMPUTATIONAL PHYSICS

OVERVIEW

Theoretical physics research is centered in the areas of atomic, nuclear, and astrophysics. The nuclear program entails research in low-energy nuclear structure and reactions, relativistic heavy-ion physics, and hadron spectroscopy. These programs are strongly tied to the Physics Division.

Research in nuclear structure and astrophysics theory has expanded to take advantage of the new opportunities presented by the joint ORNL-University of Tennessee nuclear structure and astrophysics theory program. Investigations begun in this area include studies of drip-line properties, nuclear masses for astrophysics, high-spin states, and experimental research in numerical simulations of Type II supernova explosions.

The atomic theory program studies collision phenomena over a wide range of energies using powerful new mathematical and computational methods. Particular attention is focused on complex systems such as highly charged ions, which play a leading role in many branches of energy research. The program has strong interactions with the experimental atomic collision programs at ORNL and other laboratories. Many of our applications rely on access to supercomputers, notably the NERSC Crays, and the massively parallel Intel Paragon at ORNL. We have devoted much effort to developing algorithms which efficiently use the special features of these architectures.

ASTROPHYSICS

NEUTRINO-DRIVEN CONVECTION IN CORE COLLAPSE SUPERNOVAE

A. Mezzacappa, A. C. Calder,[1] S. W. Bruenn,[2] J. M. Blondin,[3] M. W. Guidry,[4] M. R. Strayer, A. S. Umar[5]

Current core collapse supernova modeling centers around the idea that the stalled supernova shock wave, which is generated by stellar core collapse and rebound, is reenergized by electron neutrino and antineutrino absorption on nucleons behind it,[6] and that this process is aided by convection. One potentially important mode is neutrino-driven convection directly below the shock.[7]

We have coupled state-of-the-art (PPM) two-dimensional hydrodynamics to realistic one-dimensional (multigroup flux-limited diffusion) neutrino transport to investigate neutrino-driven convection.[8,9] We have investigated its development, evolution, and ramifications for the explosion mechanism, for both 15 and 25 solar mass models, representative of the two classes of stars: those with compact or "fat" iron cores, respectively. We see large-scale convection develop behind the shock, characterized by high-entropy, mushroom-like, expanding upflows and dense, low-entropy, finger-like downflows (see Fig. 5.1). The upflows reach the shock and distort it from sphericity. However, despite the appearance of violent neutrino-driven convection in our simulations, the shock eventually recedes, and by ~500 ms after bounce there is no evidence of an explosion or of a developing explosion. We conclude that, with increased sophistication in neutrino transport relative to what has been implemented by other groups, neutrino-driven convection does not yield explosions.

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2. Florida Atlantic University, Boca Raton.
3. North Carolina State University, Raleigh.
4. Adjunct staff member from University of Tennessee, Knoxville.
5. Vanderbilt University, Nashville, TN.
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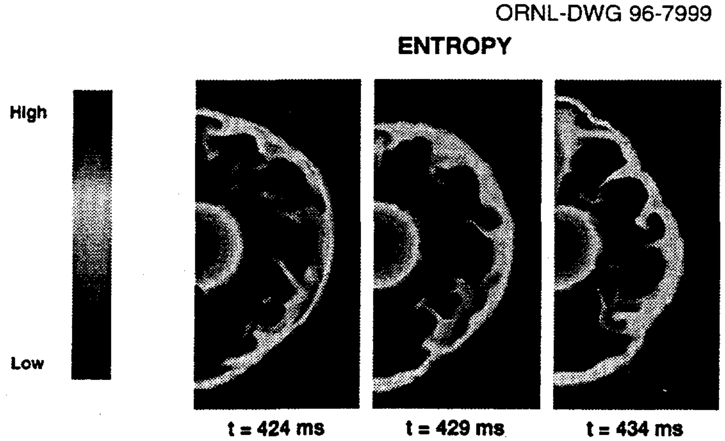

Fig. 5.1. Two-dimensional entropy snapshot at ~120 ms after bounce in our 15 solar mass simulation. Large-scale neutrino-driven convection with hot, high-entropy, expanding upflows and cold, low-entropy, dense downflows is evident.

DECIPHERING CORE COLLAPSE SUPERNOVAE: IS IMPROVED NEUTRINO TRANSPORT THE KEY?

A. Mezzacappa, O.E.B. Messer,[1] S. W. Bruenn,[2] M. W. Guidry[3]

We have computed stationary-state, three-flavor Boltzmann transport (exact) and multigroup flux-limited diffusion (MGFLD; approximate) neutrino distributions in thermally and hydrodynamically frozen time slices obtained from realistic core collapse and bounce simulations that implement Lagrangian hydrodynamics and MGFLD.[4,5] For both transport methods, the electron neutrino and antineutrino luminosities, RMS energies, and inverse flux factors, all of which enter the postshock neutrino heating rates and are crucial to reviving the stalled supernova shock, are computed as a function of radius, and compared, as well as the electron neutrino and antineutrino *net* heating rates. We find that both the electron neutrino and electron antineutrino inverse flux factors, which describe how forward-peaked these neutrinos are in the regions between their respective neutrinospheres and the shock, differ between the two transport calculations by as much as ~30%, which translates to an equal difference in heating rates. Moreover, for both flavors of neutrinos, we find a *net* heating rate for Boltzmann transport that is ~2-3 times greater in the regions directly above the gain radii than the MGFLD rate. With a dramatic increase in net heating in the Boltzmann transport calculations and with this increase occurring at the base of the net heating regions between the gain radii and the shock, we anticipate that Boltzmann neutrino transport will (1) yield much greater shock reheating and an increased probability of explosion in the absence of convection, and (2) when coupled to two-dimensional hydrodynamics, yield more vigorous neutrino-driven convection. In the latter case, the combination of increased net heating and neutrino-driven convection will also increase the probability of shock revival.

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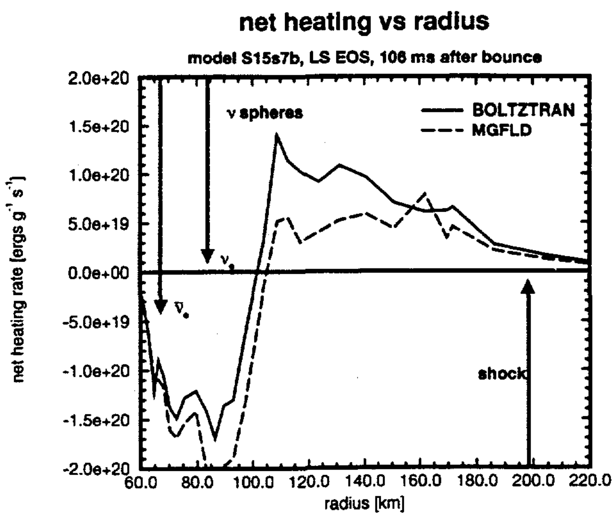

Fig. 5.2. Plot of net neutrino heating vs. radius in the region between the neutrinospheres and the shock for stationary-state Boltzmann and MGFLD neutrino distributions at about ~100 ms after bounce.

ION-ION CORRELATIONS, NEUTRINO OPACITIES, AND CORE COLLAPSE SUPERNOVAE

S. W. Bruenn[1] *and A. Mezzacappa*

The destabilization and collapse of the core of an evolved massive star initiates a complex and incompletely understood chain of events that leads in some cases to the violent expulsion of its mantle and envelope in a supernova explosion. The outwardly propagating shock ("bounce shock") launched at core rebound and rejuvenated during a reheating eipsode ultimately generates the explosion. The strength of the shock at formation, and therefore much of the postshock core structure and dynamics, is governed by the hydrodynamics of the core during infall, which is a sensitive function of the evolution of the lepton [electron and electron neutrino (ν_e)] sea, which in turn is a function of the neutrino opacities. Most of the core material during core collapse is in the form of heavy nuclei, which results in the isoenergetic coherent scattering of ν_e's on nuclei being the dominant neutrino opacity source.

Because ν_e-nucleus elastic scattering involves ν_e scattering from constituents (nucleons) with no change in their quantum states, the superposition principle applies, *viz*., the resulting amplitude is a sum over constituent amplitudes. When these constituent amplitudes are all in phase, the cross section, which goes as the square of the amplitude, becomes large.[2] However, several important corrections must be considered. One correction arises when the summation over amplitudes is extended to other nuclei (ions). This results in a multiplicative correction, which is referred to as the "ion-ion structure function." When the positions of the ions are correlated (in the extreme case, they arrange themselves into a lattice), because of destructive interference of the constituent amplitudes the ion-ion structure function reduces $\sigma_{\sigma+A}$ substantially below $\sigma_{\nu+A}^{naive}$ at low neutrino energies (i.e., neutrino energies for which $\lambda_\nu > a$, where a is the inter-ion spacing). The constituent amplitudes in this case are the amplitudes from each ion.

The effect of including the ion-ion correction, $\langle S_{ion}(\varepsilon)\rangle$, was briefly discussed by Bruenn.[3] His Fig. 4 presents a comparison of the results of core infall calculations with and without $\langle S_{ion}(\varepsilon)\rangle$, and indicates that $\langle S_{ion}(\varepsilon)\rangle$ leads to a modest increase in the deleptonization of the core: $\Delta Y_\ell = -0.02$, where ΔY_ℓ is the difference between the trapped Y_ℓ with and without $\langle S_{ion}(\varepsilon)\rangle$. Recently, Horowitz[4] introduced a fitting formula for $\langle S_{ion}(\varepsilon)\rangle$ based on Monte Carlo calculations. He argued that the substantial reduction in $\sigma_{\nu+A}^{naive}$ effected by $\langle S_{ion}(\varepsilon)\rangle$ for low-energy neutrinos would lead to a catastrophic deleptonization of the core during infall, as higher-energy ν_e's are downscattered into a low-energy, ν_e-transparent window by ν_e-electron scattering, and then freely escape.

We[5] have derived an expression for $\sigma_{\nu+A}$ that elucidates the origin of both the nuclear form factor and the ion-ion structure function $\langle S_{ion}(\varepsilon)\rangle$. We have carried out comparisons of the results of core infall simulations with and without $\langle S_{ion}(\varepsilon)\rangle$ $\langle S_{ion}(\varepsilon)\rangle$ in $\sigma_{\nu+A}^{naive}$, and with $\sigma_{\nu+A}$ turned off altogether. We have developed a simple analytical model that reproduces the numerical results and illustrates why the inclusion of $\langle S_{ion}(\varepsilon)\rangle$ in $\sigma_{\nu+A}$ does not result in a catastrophic deleptonization of the core.

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MODELING SUPERNOVA SPECTRA WITH IMPROVED ATOMIC COLLISION DATA

W. Liu,[1], D. J. Jeffery,[1] P. S. Krstic,[1] D. R. Schultz

Supernovae are the spectacular ending to the lives of a variety of stars. In these explosions, the heavy elements synthesized through fusion of lighter elements are dispersed into the interstellar medium. There they are fed back into star formation and become the primordial material of rocky planets such as earth and of the only kind of life we know. The understanding of these violent cosmic phenomena is crucial to our knowledge of the evolution of the universe and life.

Almost all our knowledge of supernovae is extracted from the interpretation of their light: time-dependent spectra and luminosity. Recent advancements in observations such as obtained with the *Hubble Space Telescope* have provided us with supernova spectra of unprecedented quality. Interpretation of these spectra requires sophisticated modeling of atomic processes which will place more stringent constraints on supernova explosion mechanisms. To model supernova spectra and determine the most likely explosion mechanism, we are developing sophisticated computer codes to analyze the atomic processes such as ionization, heating, and cooling, and to determine the atomic level populations in supernova ejecta. The accuracy of the calculations depends critically on the accuracy of the atomic data. Therefore, in parallel with our new modeling efforts, we are calculating and collecting the best available atomic cross sections and rates for collision processes, particularly electron-impact excitation and ionization of and charge transfer among iron-group atoms and ions in low charge states.

Recently, we have demonstrated the importance of including dominant atomic processes with reliable atomic collision data in supernova modeling. Figure 5.3 shows the abundances of neutral and ionized iron, which is the dominant element for velocities below about 9000 km s^{-1}, as a function of expanding velocity of Type Ia supernova ejecta. It illustrates the difference in the ionization structure of Type Ia supernovae when charge transfer is neglected (top panel) and when it is included (bottom panel). The difference compels us to conclude that charge exchange, hitherto neglected in supernova modeling, is essential for understanding supernova spectra.

We expect that our state-of-the-art modeling incorporating accurate and complete atomic data will significantly improve the understanding of supernova spectra, and thereby the understanding of the supernova explosion mechanisms and explosive nucleosynthesis.

1. ORISE Postdoctoral Research Associate.

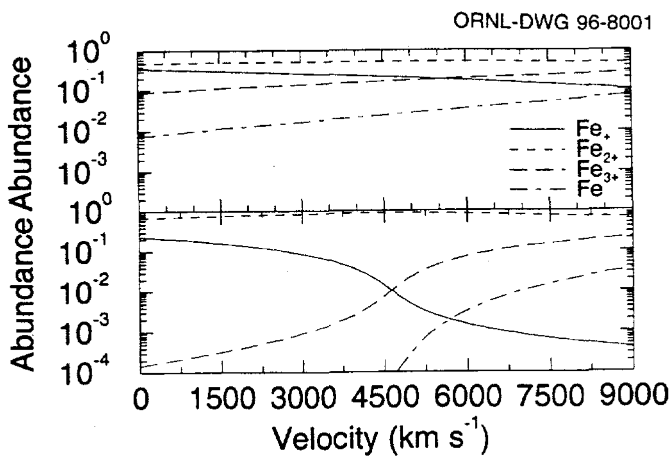

Fig. 5.3. Ionization structure of Type Ia supernovae.

ELECTRON CAPTURE RATES FOR NUCLEI IN THE IRON REGION

D. J. Dean, P. B. Radha,[1] S. E. Koonin,[1] K. Langanke,[1] M. Jeng[1]

Electron capture in the core of the presupernova is important in determining the evolution of the core. Neutrinos are the products of such processes and can transport energy away from the core. In addition, the mass-to-charge ratio of the star, which is significantly affected by such charge-changing processes, determines the size of the core at collapse and hence the fate of the star. Inputs to supernovae codes for electron capture are based on the ideas of Fuller, Fowler, and Newman, which involve placing the independent particle strength at a single energy, determined (again) by the independent particle picture. However, experimental studies show that this strength is significantly suppressed compared to the independent particle picture, as well as fragmented, the strength being distributed over several states.

One can obtain strength functions from imaginary time-response functions through an inverse Laplace transform. We have applied a maximum entropy procedure to extract GT strength functions from imaginary time-response functions calculated using SMMC methods. Our results have been validated for the lower pf-shell nuclei, where complete $0\hbar\omega$ direct diagonalization calculations are possible. Although we cannot produce detailed distributions, the positions of the peaks and the widths of the distributions compare well with experimental strengths obtained from (n,p) or (p,n) reactions for all the nuclei whose distributions have been measured.

Hence, electron capture rates that are mediated by this distribution can be calculated more reliably than current rates used in supernovae models. Our preliminary results indicate that, for ground states, these GT strength functions can provide electron capture rates to within a factor of two of the experimental rates. Calculations at a finite temperature (that of the presupernova core) are possible and ongoing using the SMMC. In addition, the SMMC can predict the strengths of unstable nuclei or nuclei whose experimental strengths are not known.

This continuing project involves calculating the electron capture rates for the thirty or so nuclei in the iron region that are expected to play an important role in supernovae studies. The implications of our results will become apparent after these rates have been calculated for all of the relevant nuclei. An example of some of the calculated strength distributions compared to experiment is shown in Fig. 5.4.

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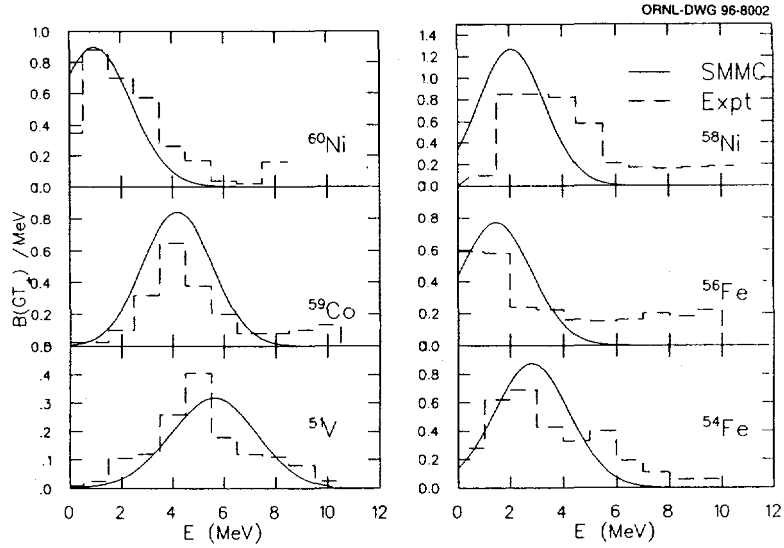

Fig. 5.4. Shown are results of SMMC calculations (solid line) of Gamow-Teller strength distributions compared to experiment (dashed line) for various nuclei.

SHELL-MODEL STUDIES FOR DARK MATTER DETECTORS

D. J. Dean and M. T. Ressell[1]

The identification of the dark matter known to exist in our galaxy, and beyond, is one of the foremost challenges confronting physicists and astronomers today. A *highly* favored hypothesis is that the dark matter consists of weakly interacting massive particles (WIMPs) called neutralinos χ, which arise in supersymmetric (SUSY) extensions of the standard model of particle physics. The extreme attractiveness of this scenario has given rise to numerous experimental efforts attempting to discover these neutralinos.[2] Two of the most popular detector materials are crystals of NaI and liquid or gaseous Xe. (There are at least three experimental efforts using NaI and two using Xe.) Both xenon and iodine are quite heavy, and therefore, complicated nuclei that are quite difficult to model. We are performing nuclear shell-model calculations aimed at reducing the uncertainties in the χ-N scattering rates due to the poorly known structure of these nuclei.

χ-N scattering has two distinct channels. The scalar, or spin-independent, channel does not strongly depend upon detailed nuclear structure issues. Scattering via the axial, or spin-dependent, channel is highly dependent upon the exact distribution of the spin density of the nucleus. At small momentum transfers, the measured magnetic moment, μ, provides a hint to this spin structure. Unfortunately, for heavy nuclei like iodine and xenon, χ-N scatterings are likely to have momentum transfers that are of the order of the inverse nuclear size and larger. Thus, the spin response function, of form factor, must be extracted. There is no known, measurable, process which is sufficiently similar to χ-N scattering to provide information on axial χ-N scattering at finite momentum transfers; therefore, detailed nuclear structure calculations are required. To date, no satisfactory model of the nuclei ^{127}I or ^{129}Xe has appeared in the literature. Our approach to modeling these nuclei is to use the conventional nuclear shell model in extremely large model spaces. Calculations of this size and complexity have only recently become possible due to advances in computer hardware and the algorithms that we depend on. There are no readily available and well-tested Hamiltonian interactions for this mass range, so we have examined two different effective interactions, each derived from a different nucleon-nucleon scattering potential.

Inserting these interactions into our large model space calculations, we have been able to generate nuclear wave functions which reproduce a number of nuclear observables, including the important magnetic moment, quite well. With these wave functions in hand, it is a straightforward exercise to calculate the nuclear spin response of the nuclei: ^{127}I, ^{129}Xe, ^{131}Xe, and ^{125}Te to scattering with an arbitrary neutralino.

Preliminary results indicate that our form factors are quite different than the *an satzes* previously adopted by the experimental groups in the analysis of their data. Experimentalists involved with each of the three NaI experiments currently running have expressed interest in using these results in the next analysis of their data.

The element ^{127}I seems well suited to experiments in particle astrophysics.[3] Not only is it a major component in the experiments above, it is also being developed as a detector for solar neutrinos. Once again, unknown nuclear structure issues are causing confusion for this effort. The solar ν capture (Gamow-Teller) reaction $^{127}\mathrm{I}(5/2^+)_1 + \nu_e \rightarrow {}^{127}\mathrm{Xe}(3/2^+)_1 + e^-$ is an excellent candidate transition to measure ^{7}Be neutrinos coming from the sun. Unfortunately, no calibration of this transition is available. Using our expertise in modeling iodine and the xenon isotopes, we are performing shell-model calculations of the above-mentioned transition. To test and illustrate the effectiveness of this technique, we intend to calculate similar Gamow-Teller transitions in neighboring nuclei where they have been measured. If we can accurately reproduce these similar transitions, it will validate our calculations of the $^{127}\mathrm{I}(5/2^+)_1 + \nu_e \rightarrow {}^{127}\mathrm{Xe}(3/2^+)_1$ transition and allow us to provide an overall normalization/calibration for the iodine solar-neutrino experiment.

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ATOMIC PHYSICS

WAVE FUNCTIONS FOR THREE CHARGED PARTICLES

J. H. Macek[1] and S. Y. Ovchinnikov[2]

Wave functions for three charged particles are central to the theory of ion-atom collisions, electron correlations in atoms, and the breakup of molecular systems into three charged fragments. The profound effects of electron correlation are exemplified by Wannier's threshold law for the ionization of neutral atoms by electron impact.[3] Here it is found that electron correlations in the final state depress the cross section and give rise to a power law E^{ζ_W} where the exponent ζ_W is neither an integer nor a half-integer. While this law is well established experimentally,[4] standard *ab initio* methods do not obtain cross sections in accord with this result, primarily because such methods are not suitable for treating the interactions of particles at long range.

We have developed an *ab initio* method[5,6] that is able to treat three charged particles at all distances including the large distances relevant at low energy. The method employs a set of Sturmian basis functions $S(\nu;\Omega)$ and eigenvalues $\rho(\nu)$ that adapt to the electron correlations by diagonalizing the interaction potential in hyperspherical coordinates R,Ω. The eigenfunctions have the property that, at well-defined hyper-radii R, their eigenvalues define an effective centrifugal potential

$$V(R) = \frac{\nu^2 - 1/4}{R^2} \tag{1}$$

where ν is a parameter. Corresponding to this potential, the motion in R is represented by a Bessel function $Z_\nu(KR)$. The complete expression for the wave function is

$$\psi(R,\Omega) = \sum_n \int_{-\infty}^{\infty} R^{1/2} Z_\nu(KR) A_n(\nu) S_n(\nu;\Omega) d(\nu^2). \tag{2}$$

The representation in Eq. (2) involves both a sum over basis functions and an integral over the index ν. Practical computations involve truncating the sum to a managable number of terms. One notable feature of this representation is that a complete S-matrix is obtained no matter how few terms are employed. Furthermore, it appears that the sum converges rapidly, and that accurate results are obtained with just one basis function. This representation is used to examine several physical processes of current interest.

1. UT-ORNL Distinguished Scientist.
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THEORY OF ELECTRON IMPACT IONIZATION OF ATOMIC HYDROGEN

J. H. Macek[1] and S. Y. Ovchinnikov[2]

Electron impact ionization of atomic hydrogen has been analyzed using the Sturmian theory developed by us.[3] This process provides a stringent test of theory, since it is known that electron correlations dominate in the threshold region. As a first test, we have computed the Wannier index ς_W using a single basis function. In this case a simple physical picture for the ionization process emerges. A wave propagates from the origin outward in R. As it propagates, a portion of the wave sits at the point of unstable equilibrium where both electrons are equidistant from, and on opposite side of, the nucleus. Here the potential has a saddle point and the basis functions are harmonic oscillator eigenfunctions with complex argument.

Electron motion near the saddle is represented in terms of complex harmonic oscillator energy eigenvalues

$$\varepsilon(R) \approx -C_0 / R - C_1 / R^{3/2} + ... \tag{1}$$

where C_1 is a complex number related to the saddle point of the potential.

Analytic, semiclassical expressions for ionization S-matrix elements, namely

$$S = \exp\left[i \int_{R_i}^{R_f} K(R) dR \right] \tag{2}$$

where $K(R) = \sqrt{2[E - \varepsilon(R)]}$, are obtained by evaluating the integral expression for the wave functions in the stationary phase approximation. Using this expression, we find[3] a Wannier index ς_W equal to 1.104 which differs by 2% from the accepted value of 1.127. The absolute cross section was also computed in the same approximation and found to agree with measured values within 10%. Finally, spin asymmetries were computed and found to agree within 20% of the measured values.

Owing to the steady increase of computer speeds, several *ab initio* methods have yielded what are hoped to be exact results. A model interaction which replaces the electron-electron potential by its spherical average is often used as a test of the computational techniques.[4-7] None of the computations fit the expected $E^{3/2}$ law. In addition, the time-dependent methods seemed to indicate that the coordinate space wave functions were concentrated in regions of space where the potential is smallest rather than near the charge centers where the electron-atom interaction is strongest. An analysis of the threshold region using classical mechanics[8] obtains the surprising result that the threshold is offset by 4.5 eV, i.e. ionization does not occur in this model until the energy is 4.5 eV above the true threshold.

To clarify the situation, we computed the cross section using our asymptotic Sturmian theory. We find that the threshold cross section for the spherical average model is not a power law, rather it is an exponential law of a most unusual form, namely,

$$\sigma \propto \exp\left[-aE^{-1/6} + bE^{1/6} \right], \tag{3}$$

where a and b are positive constants. The exponential suppression of $\sigma(E)$ for small E represents the quantal counterpart of the classical offset.

1. UT-ORNL Distinguished Scientist.
2. Guest assignee from University of Tennessee, Knoxville.

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THEORY OF ION-ATOM COLLISIONS

J. H. Macek[1] and S. Y. Ovchinnikov[2]

Ionization of atoms by ion impact involves the motion of three charged particles in the final state. For such processes, it is a good approximation to represent the ion motion by a classical trajectory and to compute the electron motion using the Schrödinger equation for one particle in a time-dependent potential. This representation holds over a very large energy range including a range where the ion velocity v is much less than the mean velocity of an electron in the initial state. The low velocity region has been particularly difficult to compute from first principles owing to the slow convergence of conventional basis set expansions, and to the difficulties inherent in separating ionization channels from excitation channels numerically. For this reason, we have adapted the Sturmian method to time-dependent problems.[3]

The Sturmian method that we develop employs a transformation of the Schrödinger equation so that only one coordinate R(t) measures the size of the system.[4] The coordinates of the electrons $q = r/R(t)$ are dimensionless. A new time variable $d\tau = dt/R^2(t)$ is also introduced, and finally the wave function is transformed. A Sturmian basis set $S(\omega;q)$ is defined such that the functions satisfy outgoing wave boundary conditions for positive ω and bound-state conditions for negative ω. The solution of the Schrödinger equation is then written as

$$\varphi(q,\tau) = \sum_n \int_{-\infty}^{\infty} A_n(\omega) S_n(\omega) \exp[-i\omega\tau] d\omega \tag{1}$$

where the $A_n(\omega)$ are coefficients computed by solving a set of coupled equations.

As in the case of electron impact, we examine the one-Sturmian approximation and evaluate the integral over ω in the stationary phase approximation. This gives the hidden-crossing expression[5] for any S-matrix element

$$S_{f_i} = \exp\left[-\mathrm{Im}\frac{1}{v}\int_{R_i}^{R_f} \varepsilon(R)dR\right], \tag{2}$$

where $\varepsilon(R)$ is a multivalued function such that when R is real, the different branches of the function are the energy eigenvalues at fixed R. The integral is taken along a path that starts on the i'th branch.

This formula is illustrated schematically in Fig. 5.5. Integrating the phase along the real axis gives the elastic scattering phase shift while integrating around the branch point gives the WKB S-matrix element for transitions from i to f.

To apply this theory to ionization, it is necessary to find paths that lead from the initial state, past all crossings related to excitation and eventually into a region that can be identified with ionization. This region has been found in our computations and corresponds to electrons moving near the saddle point of the potential.[3]

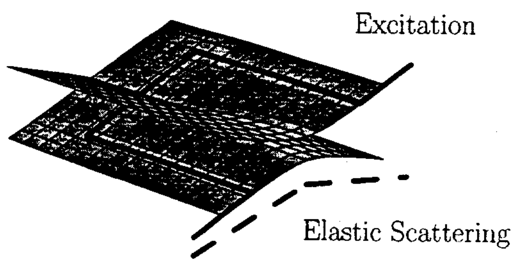

Fig. 5.5. Schematic paths of integration to compute elastic scattering and excitation.

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1. UT-ORNL Distinguished Scientist.
2. Guest assignee from University of Tennessee, Knoxville.

3. S. Y. Ovchinnikov and J. H. Macek, *Phys. Rev. Lett.* **75**, 2474 (1995).
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ELECTRON DISTRIBUTIONS IN ION-ATOM COLLISIONS

J. H. Macek[1] *and S. Y. Ovchinnikov*[2]

Electron energy distributions in low-energy ion-atom collisions are particularly difficult to compute owing to the large distance and time scales involved in the ionization process. We show that the Solov'ev-Vinitsky[3-5] wave function $\varphi(q,\tau)$ yields an extremely trivial formula for the ionization amplitude A(k), where k is the electron momentum, namely,

$$A(k) \approx \varphi(k/v,0). \quad (1)$$

In essence, the Schrödinger equation for the wave function $\varphi(q,\tau)$ becomes an equation for an ionization amplitude with the scaled coordinate q replaced by the velocity-scaled electron momenta k/v. The physical ionization amplitude emerges at the $t \to \infty$, or equivalently the $\tau \to 0$ limit. This happens because in scaled coordinates all of the bound-state contributions vanish as $\tau \to 0$, leaving only the ionization component.

We have used Eq. (1) to compute electron distributions for 4 keV proton impact on atomic hydrogen. The calculated electron distribution shows the continuum capture cusp when k = v and the direct ionization cusp when k = 0 in the laboratory frame. These features are present in all measured electron momentum distributions but have not previously been obtained in *ab initio* computations for low-velocity ion impact.

In addition to the expected cusp features, our distributions in Fig. 5.6 show a broad distribution characteristic of saddle point motion. This distribution is concentrated between the two cusps, and is fairly flat in directions parallel to the incident ion velocity v. It is strongly peaked in directions perpendicular to v, with distributions that are approximately Gaussian. To further investigate this distribution, we have computed it for 5, 10, and 15 keV proton impact on atomic hydrogen at an impact parameter of 1.8 a.u. The results exhibit a rapid variation of the distribution with ion velocity. This rapid variation is traced to the slow decrease of the real part of $\varepsilon(R) \propto R^{-3/2}$ for complex values of R. In essence, the rapid variation is a physical manifestation of the function $\varepsilon(R)$ for complex R.

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1. UT-ORNL Distinguished Scientist.
2. Guest assignee from University of Tennessee, Knoxville.
3. S. Y. Ovchinnikov and J. H. Macek, *Phys. Rev. Lett.* **75**, 2474 (1995).
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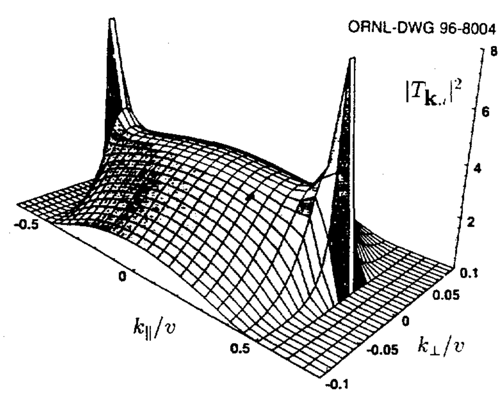

Fig. 5.6. Computed electron distributions for proton impact on atomic hydrogen showing cusps when electron momenta match the proton momenta and the top-of-barrier electrons between the cusps.

ELECTRON EMISSION FROM SURFACES

C. O. Reinhold and J. Burgdörfer[1]

The study of kinetic electron emission in ion-solid collisions provides an important link between atomic physics and condensed matter physics. Comparative analysis of spectra from ion-atom, ion-solid (transmission) and ion-surface (glancing incidence) collisions affords the opportunity to extract detailed information about long-range image interactions and multiple scattering in the solid and near the surface. As a consequence of the image the impinging projectile, recent experiments have found that the convoy peak, well known from ion-atom and ion-solid collisions, is dramatically broadened and shifted in energy.

We have developed a microscopic model to study emission of fast electrons in glancing-angle ion-surface collisions using a classical trajectory Monte Carlo approach.[2-4] Our model accounts for both dynamic image interactions and multiple scattering near the surface and predicts a pronounced convoy electron peak for small emission angles. We find that the position and shape of the convoy peak are determined by rainbow scattering of electrons in the dynamically screened field of the ion. Figure 5.7 illustrates the dramatic effects introduced by the projectile image potential V_{pe}^{I}. Inclusion of this interaction shifts the highest density region from $v_e \cong v_p$ to $v_e > v_p$ and causes a pronounced void in the forward electron spectrum near the region $v_e \cong v_p$. This depletion is a direct consequence of the expulsion of ejected electrons by the repulsive image potential.

Concerning the shape of the ejected electron spectra, good agreement has been found with recent experiments obtained at Kyoto University for 0.2-0.5 MeV/u Li ions interacting with SnTe(001) surfaces.[2] However, preliminary normalization of the experimental spectrum indicates that the calculation may overestimate the absolute yield of electrons in a large amount. At this moment, no convincing explanation can be put forward to reconcile this discrepancy. Experiments currently under way at ORNL using Si targets[5] may shed some light on this problem. During the next year, we plan to produce the first comparison of calculated and measured absolute yields of convoy electrons.

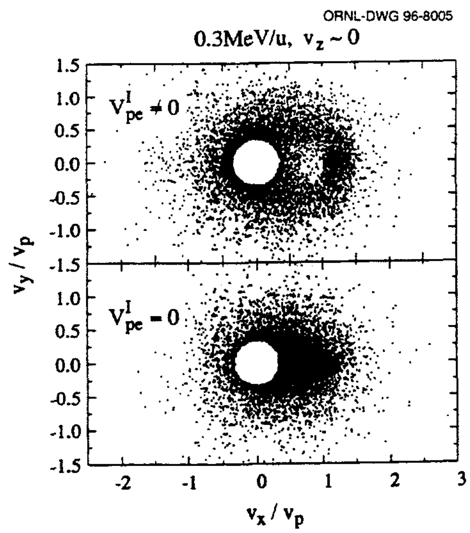

Fig. 5.7. Effect of the image potential V_{pe}^{I} on the spectrum of ejected electrons. The figure shows a density plot in velocity space of ejected electrons arising from 0.3 MeV/u Li-SnTe collisions cut in the (v_x, v_z) plane. The solid is contained in the $z < 0$ region, the surface is contained in the (x,y) plane, and the ion trajectory is contained in the (x,z) plane.

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1. Adjunct staff member from the University of Tennessee, Knoxville.
2. C. O. Reinhold et al., *Phys. Rev. Lett.* **73**, 2508 (1994); *Nucl. Instrum. Methods Phys. Res. B* **115**, 233 (1996); *Nucl. Instrum. Methods Phys. Res. B* **99**, 50 (1995); *Nucl. Instrum. Methods Phys. Res. B* **100**, 378 (1995).
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DYNAMICS OF RYDBERG ATOMS IN HALF-CYCLE PULSES

C. O. Reinhold and J. Burgdörfer[1]

Recently, the generation of "half-cycle" electromagnetic pulses (HCPs) in the terahertz,[2] gigahertz,[3] and megahertz[4] regime has been achieved. They are characterized by a strong unidirectional electrical field confined to a very short time interval. Such pulses provide a novel tool to study the non-perturbative dynamics of Rydberg atoms in the region where the duration of the pulse T_p is of the order of the classical period of the atom T_{n_i}. This is an ideal problem to probe the correspondence between the classical and quantum mechanical time-dependent dynamics of the electron in the atom.

Motivated by these advances, we have developed classical, semiclassical, and quantum mechanical approaches to study the dynamics of Rydberg atoms in the short pulse regime. We have studied the ionization dynamics of extreme parabolic states as a function of the field strength and the duration of the pulses. We have predicted novel classical and quantum time-dependent phenomena and have compared our calculations with experiments performed at the University of Virginia and the University of Michigan using picosecond pulses.[5,6]

More recently, we have established a collaboration with experiments at Rice University using nanosecond pulses.[7,4] Wavepackets comprising a superposition of very high-lying Rydberg states have been created using a short HCP. The properties of the wavepacket are probed using a second HCP that is applied following a variable time delay. The second pulse ionizes a fraction of the atoms and the survival probability exhibits pronounced oscillations (see Fig. 5.8) that are associated with the quasi-periodic evolution of the wavepacket. We have also produced and probed Stark wavepackets by replacing the first pulse by a field step. In the future we plan to study the dynamics of atoms subject to trains of many pulses. Interesting dynamical responses of the atoms are expected to occur when the frequency of the train is of the order of the atomic frequencies.

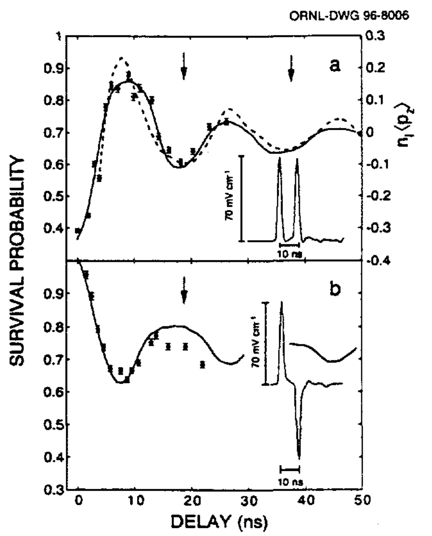

Fig. 5.8. Rydberg atom survival probability (left scale) following application of two HCPs in (a) the same, and (b) opposite senses to $K(n_i p)$ atoms with $n_i \sim 417$ as a function of time delay. •••, experimental data; ___, classical calculations. Multiples of the classical orbital period are marked by arrows. The insets show the pulse profiles. - - - (right scale) time development of the scaled expectation value $\langle p_z\rangle / p_{n_i} = n_i\langle p_z\rangle$ following application of the first HCP.

1. Adjunct staff member from the University of Tennessee, Knoxville.
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NEUTRALIZATION OF HIGHLY CHARGED IONS NEAR INSULATORS

J. Burgdörfer,[1] L. Hägg,[2] C. O. Reinhold

The interaction of slow highly charged ions (HCIs) with insulator surfaces has recently received much attention.[3-6] Earlier, the interaction of HCIs with metal surfaces has been studied in detail and a scenario for the neutralization of the HCI in front of a metal has emerged.[7] As the HCI approaches the surface, it induces an image which, in turn, accelerates the ion towards the surface (i.e. it gains energy). As soon as the potential barrier separating the electronic motion in the surface and in the ion becomes lower than the Fermi edge, electrons are transferred in classical over-barrier (COB) transitions. The interaction time has a lower bound given by the image energy gain. The neutralization of the HCI occurs by electron transfer into highly excited levels of the ion leading to the formation of so-called "hollow atoms." First results for LiF have shown similarities and differences to metals which are not yet well understood; image energy gains were found to be similar, whereas KLL Auger peaks with minimal L population were found to be missing, suggesting that hollow-atom formation is suppressed.

Work is in progress concerning the theoretical description of the interaction between HCIs and insulator surfaces.[8] Our analysis makes use of realistic electronic potentials near an insulator whose response is treated using the experimental frequency dependent dielectric function. We have modified the COB model to treat insulator surfaces and, in addition, we have developed a classical trajectory approach. The latter allows the treatment of electron capture from different ionic sites and for the finite response time for the polarization of the initial atomic orbital. For grazing incidence we have calculated the image energy gain using a modified staircase model demonstrating the existence of a weak velocity dependence for LiF which is absent for a metal (see Fig. 5.9). The local charge-up of the insulator surface is taken into account as a deceleration of the HCI. Our calculated values are close to the experimental results.

In order to estimate the efficiency of the formation of hollow atoms for HCIs impinging on LiF and draw conclusions about KLL Auger transitions, the complete capture sequence needs to be studied in more detail. A major difficulty is the complicated dependence of the potential on the history of the neutralization sequence, i.e. from which sites previous capture events have taken place. The local distribution of the microscopic charge-up may be crucial in determining the efficiency of hollow-atom formation.

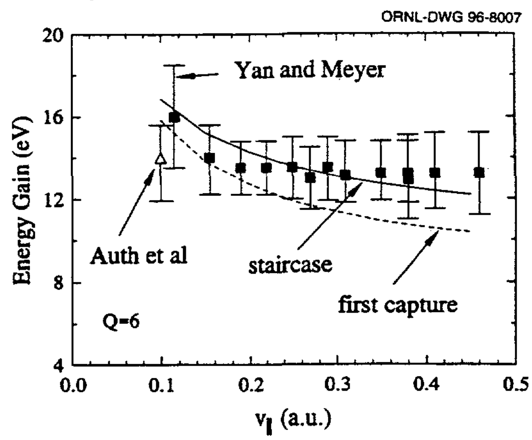

Fig. 5.9. The energy gain for LiF as a function of the velocity $v_{\parallel}$ for a grazing incidence HCI with initial charge Q = 6. Experimental values are from Refs. 3 and 4.

1. Adjunct staff member from the University of Tennessee, Knoxville.
2. Stockholm University, Stockholm, Sweden.
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STRIPPING OF RELATIVISTIC H⁻ BEAMS BY THIN FOILS

B. Gervais,[1] *C. O. Reinhold, J. Burgdörfer*[2]

The stripping of H^- to protons by foil transmission at ≅ 1.2 GeV is the cornerstone of all competing designs for the beam injection into next-generation pulsed spallation neutron sources (SNS). The limited efficiency for charge-changing from H^- to H^+, the accompanying emission of high-energy electrons, as well as angular straggling of the transported beam are currently thought to represent major sources of beam loss. A fraction of H^0 exits the foil in excited states which then gets stripped by the strong magnetic field in the first bending magnet and collide with walls and magnets. These losses represent a high source for radioactivity along the beam line which complicates hands-on maintenance of the ring structure. The underlying physics as well as strategies to control and to reduce beam loss are not well understood.

We have acquired considerable experience in transport of excited states of hydrogen through foils at non-relativistic energies and, recently, we have begun to develop the extension of our transport theory to relativistic energies.[3] Our method employs a Monte Carlo solution of a microscopic Langevin equation. The stochastic force describes the collisions the atomic electrons of H^0 (or H^-) suffer with the electron gas and ionic cores in the foil, while the deterministic force is derived from atomic potentials and may also include external motional electric and magnetic fields. Upon emergence, the distribution of electrons among excited n states, the substate distributions of parabolic quantum numbers $k = n_1 - n_2$ which governs field ionization rates, as well as the energy and angular-distribution of convoy electrons can be determined.

A sample calculation[3] for the excited state distribution of around 800 MeV protons as a fraction of thickness of the carbon foil and a comparison with experimental data from LAMPF[4] are presented in Fig. 5.10. The conversion from H^- to H^+ proceeds in a two-step process of sequential collisions: $H^- \rightarrow H(n) \rightarrow H^+$. The first step predominantly populates H(n = 1,2). Subsequently, higher excited states become populated as a result of multiple scattering inside the foil.

If funding permits, we plan to continue the development of this program in order to address the underlying fundamental atomic physics, the ion-solid interactions, and the application to the neutron source design. In particular, we plan to develop classical and quantum transport simulations in the presence of a strong magnetic field.

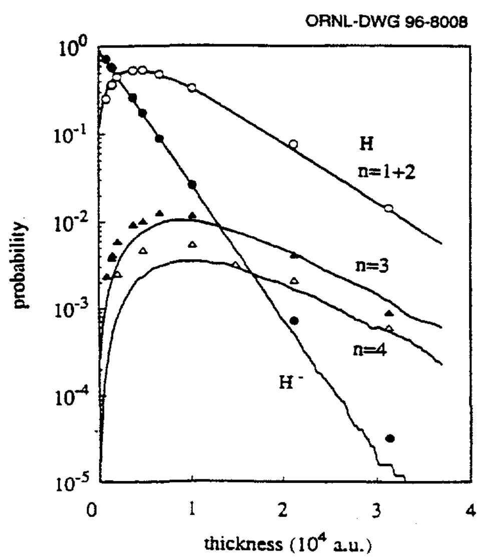

Fig. 5.10. Comparison of present classical transport simulation with absolute experimental data[4] at E_p = 800 MeV for H^-, H(N = 1+2), H(n = 3), and H(n = 4).

1. National Center for Scientific Research, Caen, France.
2. Adjunct staff member from the University of Tennessee, Knoxville.
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ANTIPROTON-IMPACT IONIZATION OF HYDROGEN AND HYDROGENIC IONS

D. R. Schultz, P. S. Krstic,[1] C. O. Reinhold, J. C. Wells[2]

Only relatively recently have intense, mono-energetic, well-collimated beams of low-energy antimatter projectiles such as positrons and antiprotons been available for the study of ion-atom collisions. The utility of these projectiles stems from the unique ability they give researchers to study the change of the collision dynamics and reaction probabilities when a single projectile characteristic is changed. That is, comparison of proton and antiproton impact reflects only a change of charge sign, whereas proton and electron impact comparisons display simultaneously a change of charge sign and mass. Considerable insight has been derived in the past decade by comparing the ratio of double to single ionization, the spectrum of electrons ejected in ionization, and the variation of the stopping power presented by antimatter versus matter impact.

Prompted in large part by very recent experiments[3] and our own previous calculations, we have made a detailed study of ionization in collisions of antiprotons with hydrogen and hydrogenic ions. The results obtained reveal a remarkable difference in the mechanisms and behavior of ionization at low collision velocity between proton and antiproton impact, and between hydrogen and hydrogenic ions as the target. The physical picture developed has been based upon our novel solutions of the time-dependent Schrödinger equation on a very large three-dimensional numerical lattice, classical electronic trajectory simulations, and analysis of the quasimolecular eigenenergy surfaces in the plane of complex internuclear separation.[4-6] Ongoing efforts seek to treat collisions with fully correlated two-electron targets so that antiproton-helium collisions can be considered. The goal is a similarly detailed description of the behavior of ionization for this collision system in light of challenges presented to theory by other recent experimental measurements.

1. ORISE Postdoctoral Research Associate.
2. Consultant from Harvard-Smithsonian Center for Astrophysics, Cambridge, MA.
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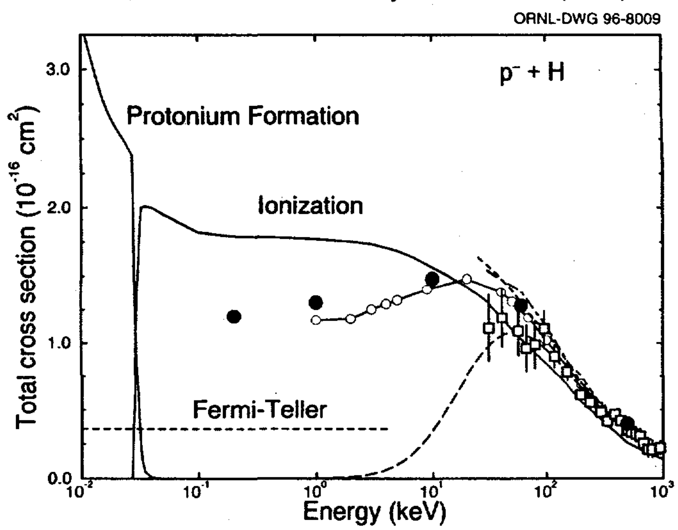

Fig. 5.11. Ionization cross section as a function of collision energy for $\bar{p}$ + H. Experimental measurements (squares[3]) are compared with various theoretical approaches: solid curve – classical trajectory, simulation circles – lattice time-dependent Schrödinger equation, long dashed curve – perturbation theory, open circles, dashed curve, and dot-dashed curve – different close coupling calculations. Also shown is the Fermi-Teller limit.

TIME-DEPENDENT LATTICE DIRECT AND CLOSE-COUPLING APPROACHES TO ELECTRON-ATOM SCATTERING

M. S. Pindzola,[1] D. R. Schultz, D. H. Madison,[2] G. Buffington[2]

Calculation of accurate electron-impact excitation and ionization cross sections remains a long-standing problem in atomic collision physics. Two of the most powerful approaches are based on time-dependent treatment of the Schrödinger equation on a numerical grid, either by solving a set of close-coupled differential equations or by direct solution of the fully correlated problem. We are pursuing both approaches and have recently applied them to the computation of excitation and ionization of atomic hydrogen by low-energy electron impact. Both approaches utilize a wavepacket method to represent the incoming electron and rely on time propagation of the total wavefunction through the collision on a spatial lattice.

In the close-coupling approach, a complete LS partial wave solution is found by extending the earlier work of Wang and Callaway[3] to the time-dependent domain.[4] The direct method was developed originally by Bottcher and co-workers[5,6] and analytically reduces the full six-dimensional, two-electron Schrödinger equation to three dimensions and a set of coupled equations of L terms, where L is the total angular momentum under consideration. Both works have obtained results that are in very good agreement with the most accurate available methods. Work is under way to extend these calculations to other systems by including model or pseudopotentials, and to treat problems involving interactions with electromagnetic fields.

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1. Auburn University, Auburn, AL.
2. University of Missouri, Rolla.
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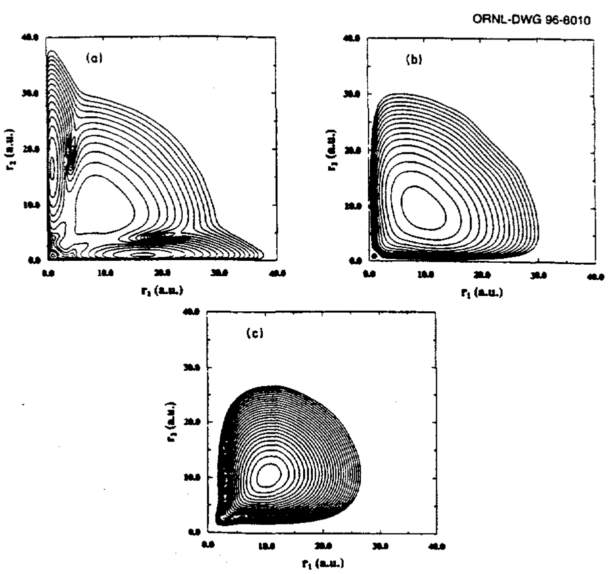

Fig. 5.12. Wavefunction for e+H scattering at 30 eV for a three-channel, time-dependent, close-coupling calculation: a) s^2, b) p^2, and c) d^2 terms.

UNEXPECTED, YET UBIQUITOUS, OSCILLATIONS IN LOW-ENERGY ION-ATOM COLLISIONS

D. R. Schultz, C. O. Reinhold, P. S. Krstic[1]

A general feature of the cross sections for excitation, ionization, or non-resonant charge transfer in ion-atom collisions is that they rise from zero, peak, and drop off as a function of increasing collision velocity. Broadly speaking, this behavior can be understood as arising from the velocity-matching of the target's orbital electron with the projectile. That is, the probability of reaction, and therefore the cross section, is small at low-collision velocity since the projectile velocity is much slower than that of the electron, increases as the projectile velocity matches that of the electron, and falls off as the collision takes place so quickly that little energy and momentum is transferred.

Several previous theoretical and experimental works have found, for low-collision velocities, a controversial oscillation of certain reaction channels for particular ion-atom collisions superimposed on this general behavior. We have found that this is, in fact, an unexpected, and so far unexplained, feature of a broad class of collision systems and channels.[2] Furthermore, we have presented our findings of a classical mechanism responsible for these oscillations and tentatively identified possible analogs within fully quantum-mechanical treatments. In brief, these oscillations are related to the coherence obtained when the electron swaps back and forth between the projectile and target through initially quasi-resonant states before being promoted (either to the excited states of the projectile or target including the continuum). Work is in progress to place this model on a more firm quantum-mechanical foundation, elucidating in more detail the scope and behavior of this, at first seemingly anomalous, phenomenon.

1. ORISE Postdoctoral Research Associate.
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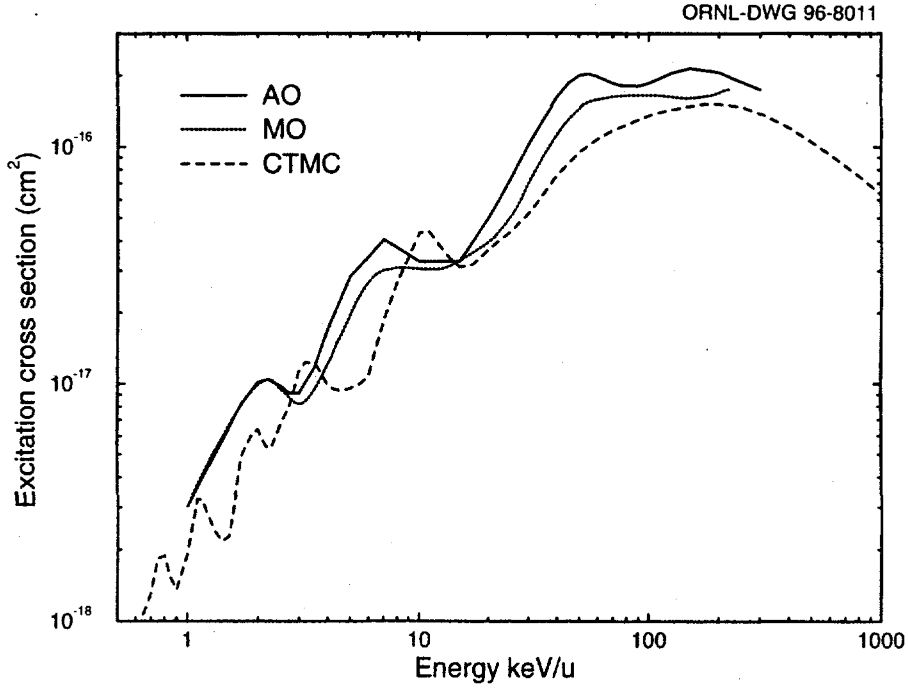

Fig. 5.13. Comparison of theories for excitation to H(n=2) by He^{2+} impact. Shown are the results of the present classical trajectory simulations (CTMC), and published atomic orbital and molecular orbital close-coupling treatments.

NUCLEAR PHYSICS

SHAPE RESONANCES IN $^{12}C + {}^{12}C$ SCATTERING AT LOW ENERGIES AND CONTINUITY WITH HIGH-ENERGY SCATTERING OPTICAL POTENTIALS

Y. Kondo,[1] D. T. Khoa,[2] G. R. Satchler[3]

A phase-shift analysis[4] of the elastic scattering of $^{12}C + {}^{12}C$ at c.m. energies from 5.5 to 33 MeV revealed gross structures interpreted as a band of shape resonances for partial waves with (even) angular momenta from L = 0 to L = 16. We have reproduced the energies of these shape resonances accurately by using simple optical potentials with deep real parts, including one generated by a "microscopic" folding model with a recently derived[5,6] realistic effective nucleon-nucleon interaction. This is the same class of potentials that has been unambiguously determined from analyses of elastic scattering angular distributions at much higher energies[6,7] which display refractive effects such as rainbows and Airy minima.

Previous studies of the scattering of light heavy ions at low energies have focused upon potentials with very shallow real parts. In contrast, our $^{12}C + {}^{12}C$ potentials have depths of about 260 MeV at the origin in this energy range. Thus they are compatible with the kind of depths required at the higher energies in order to reproduce the refractive phenomena observed. Our analysis provides an opportunity to give a unified description of the scattering in both energy ranges.

The shape resonances obtained fall into a band characterized by a given quantum number Q = 2n+L, where n is the number of nodes in the radial wavefunction. Our potentials give a band with Q = 20. The Pauli principle requires that the wavefunction for the combined system be antisymmetric. This is automatically satisfied[8] if the relative motion of the two clusters has a sufficiently large value of Q. This immediately entails that the potential be deep. Shallow potentials, on the other hand, assign n = 0, or Q = L, to the observed band and their solutions do not satisfy the Pauli principle; they correspond to forbidden states. An investigation[9] of a $^{12}C + {}^{12}C$ cluster model for the low-lying bound states of ^{24}Mg indicated that Q = 16 or greater was required. In our case, the scattering resonances correspond to a much higher excitation in ^{24}Mg ($E_x = E_{cm} + 13.9$ MeV), so that Q = 20 is quite appropriate; it is further supported by the continuity that this provides with the potentials determined by the scattering at the higher energies, using the same argument that was applied to the $^{16}O + {}^{16}O$ system.[7]

More detailed constraints on the potential are imposed by the energies at which Airy minima are observed in the 90° excitation function,[10] and these are being studied. Further information is contained in the oscillations observed in the variation of the reaction and fusion cross sections with energy.

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1. Kyoto Women's University, Kyoto, Japan.
2. Chung Yuan Christian University, Chung-Li, Taiwan.
3. Guest Assignee from University of Tennessee, Knoxville.

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INVESTIGATION OF SIGNATURE INVERSION IN DOUBLY ODD SYSTEMS

J.-y. Zhang,[1] *Y. Sun,*[1] *M. W. Guidry,*[2] *L. L. Riedinger*[2]

The anomalous inversion in staggering phase for a sequence associated with two signatures has been one of the most interesting problems in nuclear structure studies at normal deformation. A variety of theoretical efforts have attempted to understand the cause of the inversion. Current explanations for this phenomenon invoke gamma-deformation, the neutron-proton (n-p) interaction, or quadrupole pairing (q-p) forces, but none of these provides a completely satisfactory explanation of the observations.

In a 1991 paper by Hara and Sun,[3] an alternative method to study this problem was proposed. Two mechanisms of signature inversion were suggested by the projected shell model: (1) crossing of bands having opposite signature dependence, and (2) self-inversion. The former mechanism can explain the signature inversion observed in some odd-odd, rare-earth nuclei, and a predicted signature inversion systematics was confirmed by later experiments. The second proposed mechanism, self-inversion, has not yet been confirmed. Presumably, light nuclei in the mass-130 region, and some excited bands in rare-earth nuclei, could be candidates for realization of this mechanism.

With respect to the three explanations proposed in other models, the success of the axially symmetric projected shell model in explaining inversion for the rare-earth region does not indicate that explicit gamma deformation is crucial to the inversion mechanism. The projected shell model does incorporate both n-p and q-p interactions, but preliminary calculations suggest that self-inversion does not depend sensitively on these two interactions. This poses an interesting question of whether signature inversion depends on the details of the interactions, or whether it is an effect that appears naturally in the projected shell model independent of specialized parameter adjustment. We are presently testing this latter possibility by carrying out an extensive study using the projected shell model. As part of this study, a new code to calculate electromagnetic transitions for odd-odd nuclei has been constructed.

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3. K. Hara and Y. Sun, *Nucl. Phys. A* **531**, 221 (1991).

NUCLEAR MATRIX ELEMENT CALCULATED BY THE PROJECTED SHELL MODEL FOR THE DOUBLE BETA DECAY PROBLEM

J. G. Hirsch,[1] Y. Sun,[2] M. W. Guidry[3]

The detection of neutrinoless double beta decay ($\beta\beta_{0\nu}$) would imply indisputable evidence of physics beyond the standard model and would be useful in order to select grand unification theories. Theoretical nuclear matrix elements are needed to convert experimental half-life limits, which are available for many $\beta\beta$-unstable isotopes, into constraints for particle physics parameters such as the effective Majorana mass of the neutrino and the contribution of right-handed currents to the weak interaction. On the other hand, the two-neutrino mode of double beta decay is allowed as a second order process in the standard model. It has been detected in nine nuclei and has served as a testing ground for a variety of nuclear models. It is a stringent test for a nuclear model to predict $\beta\beta_{0\nu}$ matrix elements.

First estimations using a truncated shell model gave good results for some nuclei, but missed the measured half-life in others by two or three orders of magnitude. BCS approximations overestimate the matrix elements, giving half-lives that are too short. Since 1986, the quasiparticle RPA (QRPA) with an explicit particle-particle channel has been used for such calculations. However, the matrix elements depend very sensitively on the interaction parameter of this channel, so it is possible to predict any half-life by changing the parameter slightly. Even worse, the QRPA collapses (gives complex eigenvalues) for certain interaction strengths, so in some nuclei there is no prediction at all.

To describe properly the isobaric analog state and the Gamow-Teller resonance, it will be necessary for a model to include at least two major shells for protons and neutrons, with both normal and intruder orbitals, with pairing, quadrupole-quadrupole interactions, and spin-isospin interactions. It will also be necessary for it to describe deformed nuclei and to treat the doubly even and doubly odd nuclei on an equal footing. The projected shell model is clearly an ideal candidate for such a theory.

We have formulated a plan of research in this direction. The initial computer code has been completed and is being tested now.

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CONSISTENT MEAN FIELD PLUS CORRELATIONS FOR THE STUDY OF NUCLEAR STRUCTURE NEAR THE DRIP LINES

D. J. Dean, P. D. Stevenson,[1] J. R. Stone,[1] M. R. Strayer

Correlations play a significant role in the nuclear medium. For example, approximately 5-10% of the total binding energy should come from correlations. The low-lying spectrum is attributed to pair breaking in even-even systems, and the suppression of the expectation value of single-particle operators, such as the Gamow-Teller operator, relative to the naive estimate is governed by nuclear correlations. On the other hand, the charge distribution, rms radius, and a significant fraction of the mass of a nucleus are determined by the mean field. For nuclei far from stability and near either the proton or neutron drip lines, a consistent description of correlation phenomena must be included for describing these nuclei. Typical studies have been concerned with either mean-field aspects of nuclei (including a pairing mean field) or with correlation studies at the RPA level, or in the context of the shell model or simplifications thereof. We propose a different and new strategy that will lead to a more consistent description of nuclei.

Our procedure may be illustrated by considering a two-body Hamiltonian of the form

$$H(\vec{r}_1,\vec{r}_2) = -\frac{\hbar^2}{2M}\nabla^2 + t_0(1+x_0\wp)\rho(\vec{r}_1)\rho(\vec{r}_2) + g_p P^+ P + \sum_\lambda q_\lambda \sum_\mu Q_{\lambda\mu}(\vec{r}_1)Q_{\lambda\mu}(\vec{r}_2),$$

where $\wp$ is an exchange operator, P^+ is a pair creation operator for the HF states, and the final term includes all multipole interactions (quadrupole, octupole, ...) that one finds in realistic nuclei. This prescription for the Hamiltonian accounts for most of the nuclear structure aspects of the interacting system. Solving for ground-state properties perturbatively yields corrections to the ground-state energy and wave functions as a series

$$E = E_0 + E_{HF} + E_{2p\text{-}2h} + E_{3p\text{-}3h} + ...,$$

where E_0 is the vacuum state energy, E_{HF} is the contribution to the energy from the mean field, and higher-order terms enter from increasingly more complicated excitations of the system.

As a first attempt, separable two-body interactions will be studied in this framework. Other terms, such as spin- or isospin-dependent interactions will also be included as the investigation proceeds.

Our goal is to first find the Hartree-Fock ground state of such a Hamiltonian. The key ingredient here is the density-dependent interaction with parameters t_0 and x_0 determined from properties of spherical closed-shell nuclei such as ^{16}O and ^{40}Ca. The second ingredient is to go beyond the mean field by using perturbation theory techniques to investigate 2p-2h, 3p-3h, ..., excitations within the nucleus, and to calculate the contribution of correlations to the ground state and wavefunction of the system.

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ROTATIONAL AND PAIRING PROPERTIES OF ^{74}Rb

D. J. Dean, S. E. Koonin,[1] K. Langanke,[1] P. B. Radha[1]

Understanding the structure of N~Z nuclei in the mass 60-100 range is one focus of much of the experimental radioactive beam efforts currently in progress. These experiments present the possibility to study the interesting interplay of T=0 (isoscalar) and T=1 (isovector) pairing in proton-rich, medium-mass nuclei. In even-even systems, like nucleons may form either proton-proton (p-p) or neutron-neutron (n-n) pairs in ground-state configurations $T = 1, T_z = \pm 1$, where +(-)1 is for p-p (n-n) pairing. Proton-neutron (p-n) pairs may be found in either $T=1, T_z=0$, or T=0, J>0 configurations. In the same manner as p-p and n-n pairing, isovector p-n correlations in light- to medium-mass nuclei are assumed to involve a proton-neutron pair in time-reversed spatial orbitals, while the isoscalar correlations involve mainly pairing between identical orbitals and spin-orbit partners.

In order to perform a detailed study of pairing correlations, several ingredients are necessary. It is important to have exact number projection for both protons and neutrons. This ensures that a correct analysis of p-n pairing correlations can be carried out. Correlations beyond the mean field play an important role in determining both ground- and excited-state properties of a given nucleus. Thus the ultimate venue for studying p-n pairing is the shell model. Due to the increasing memory requirements of standard direct diagonalization techniques, it has been impractical to perform a detailed study of pairing correlations in medium-mass nuclei. However, shell-model Monte Carlo (SMMC) methods are well suited for such studies, and have previously been employed to investigate ground-state and thermal properties of N~Z nuclei in the pf-shell.[2] Finally, a reasonable residual interaction is required for p-n pairing studies. In this work, we use SMMC techniques to investigate the effects of rotation on the pairing correlations within the odd-odd N=Z system, ^{74}Rb. At the present time, ^{74}Rb is the only odd-odd N=Z nucleus in this region that has been studied with any spectroscopic detail.[3]

We add to the Hamiltonian a cranking term $-\omega J_z$ in order to carry out the calculation, and use a residual interaction derived from the Paris potential in the complete $1p\text{-}0f_{5/2}\text{-}0g_{9/2}$ model space. We find a band crossing from T=1 (isoscalar) to T=0 (isovector) yrast states at a critical frequency $J_{crit} = \langle J_z \rangle = 3 \pm 1.5\hbar$, consistent with experimental data. We also investigate the pairing correlations as a function of the rotational frequency of the nucleus both for low and high angular momentum. We find abrupt changes in the pairing correlations and the total B(E2) at J_{crit}.

1. California Institute of Technology, Pasadena.
2. K. Langanke et al., *Nucl. Phys. A* (in press).
3. D. Rudolph et al., *Phys. Rev. Lett.* **76**, 376 (1996).

SMMC STUDY OF RARE-EARTH NUCLEI

D. J. Dean, S. E. Koonin,[1] J. A. White,[1] W. Nazarewicz[2]

We have continued our investigations of nuclear structure in rare-earth nuclei using SMMC methods. The model space encompasses one major shell (N = 4) for protons and one major shell (N = 5) for neutrons; the shell model has never before been used for nuclei this heavy with such a large model space (32 proton states and 44 neutron states). We started by using a simple monopole pairing plus collective quadrupole interaction for a series of Dy isotopes to explore ground-state properties and nuclear shapes as A changes. The interesting physics in this region includes the microscopic description of shape transformations as one moves from the fairly spherical ^{152}Dy to the well-deformed ^{160}Dy. We anticipate that the shell-model calculations will help us understand how this deformation sets in, and how the pair content changes as one adds neutrons to the system. A further interesting study is the effect of cranking on these systems.

During the past year, we have improved the speed of our FORTRAN code by a factor of three, which has been of great benefit in this project. This has allowed canonical calculations for lower temperatures than were previously feasible; prior to this, we were largely restricted to calculations in the zero-temperature formalism. We have also expanded our interaction to include quadrupole pairing and are currently adjusting parameters to fit observed mass splittings and to determine the effective proton and neutron charges from observed $B(E2)\left(2_1^+ \rightarrow 0\right)$ values. We have used several interactions in this region: the original pairing-plus-quadrupole interaction of Kumar and Baranger, modifications to include quadrupole pairing with and without a form factor, and adjustments to the single-particle energies suggested by Onishi et al. We find that it is crucial to include the quadrupole pairing in order to obtain the correct position of the 2+ states in nuclei in this region. It is well known that in Sn isotopes one cannot obtain the first 2+ state at the correct excitation energy without quadrupole pairing. Furthermore, quadrupole pairing, while affecting the 2+ state, does not drastically affect the deformation of the system.

Once we have finished determining the interaction, our plan is to crank the system for lower spins ($I \leq 20$) to search for the first band crossing and later study pair transfer between Dy nuclei. This band crossing has been experimentally observed and is interpreted as being due to the alignment of a pair of neutrons in the $I_{13/2}$ orbital along the axis of rotation. Nuclear rotation; i.e., the cranking induces a Coriolis force acting on the nucleons which is strongest for those nucleons with higher j values. In the rare earths, the highest j-value orbitals are the unique parity intruder levels. These are $I_{13/2}$ for neutrons and $h_{11/2}$ for protons. We shall search for the crossing by examining the calculated number of neutron pairs with J = 12.

This work will form the Ph.D. thesis of J. A. White.

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MULTIPLE $\hbar\omega$ SMMC CALCULATIONS

D. J. Dean, S. E. Koonin,[1] K. Langanke,[1] M. T. Ressell[1]

Numerous problems in nuclear physics would benefit from the ability to calculate shell-model observables in more than a single oscillator shell. For example, the structure of light neutron-rich nuclei in the sd-shell requires inclusion of fp-shell orbitals in order to properly describe their deformation and cross-shell characteristics. Experimentally, this region will be probed to understand the nature of weakly bound systems, and the response of nuclei near the neutron drip line to various physical probes. Current state-of-the-art calculations often involve model spaces that allow up to $4\hbar\omega$ calculations for light nuclei, such as ^{16}O. SMMC methods allow the model spaces considered to be greatly expanded. Multi-$\hbar\omega$ SMMC calculations should be no more difficult computationally than the $0\hbar\omega$ calculations that are now routine.

When more than one oscillator shell is included, a new complication arises: excitations of the center-of-mass (CM) can get mixed into the real nuclear excitations. This leads to spurious components of wave functions being incorporated into the calculations of observables. In conventional shell-model calculations, this spuriosity is removed either by projecting out the spurious states or by adding a large multiple of the CM Hamiltonian to the normal nuclear Hamiltonian in the calculation (the Gloeckner-Lawson, or GL, prescription).

We have investigated both of these methods in the SMMC. Projection leads to another sign problem and has proven unworkable. The Gloeckner-Lawson prescription has been shown to work for fairly small CM multipliers (< 5) in comparisons with direct diagonalization calculations. Unfortunately, this method requires a "complete" $n\hbar\omega$ space to be fully effective and SMMC methods cannot work in such a complete space. The Gloeckner-Lawson prescription will still remove the spurious solutions at the cost of also slightly affecting the nonspurious solutions. The best value of the multiplier is currently being investigated. Values less than 2 seem to be best. Once the details of the CM contamination removal are resolved, several research questions will be addressed.

We are currently looking into the N=20 shell closure for very neutron-rich nuclei. We investigate how exact the shell closure really is for nuclei such as ^{32}Mg. (In the sd-pf shell, this calculation allows excitations of up to $16\hbar\omega$.) Experimentally, ^{32}Mg is highly deformed. An sd-shell calculation gives roughly 30% of this deformation, while the inclusion of the fp-shell yields the remaining deformation due to two-particle excitations into the fp-shell.

We also intend to investigate Gamow-Teller quenching in these multi-$\hbar\omega$ model spaces. We also plan to consider the possibility of working in partially complete $n\hbar\omega$ spaces and examining forbidden weak operators in light nuclei. For example, looking at ^{16}O and ^{12}C in the model space s-p-sd-pf should allow the Gloeckner-Lawson prescription to completely remove any 1 and $2\hbar\omega$ CM excitations that would mimic first forbidden operators, while not seriously distorting the model space. Only further investigation will reveal whether the above assertion is true.

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PAIRING AT THE N~Z LINE

J. Gary,[1] D. J. Dean, S. Mizutori,[2] W. Nazarewicz,[3] W. Satula[4]

Proton-rich radioactive ion-beam facilities offer the novel possibility of exploring the structure of nearly self-conjugate (N~Z) nuclei in the medium-mass range $Z \leq 50$. Special interest will be devoted to understanding the proton-neutron (p-n) interaction, which has long been recognized to play a particularly important role in N=Z nuclei. The p-n correlations can either correspond to isovector (T=1) or isoscalar (T=0) pairs. Like proton-proton (p-p) and neutron-neutron (n-n) pairing, isovector p-n correlations in light to medium-mass nuclei are assumed to involve a proton-neutron pair in time-reversed spatial orbitals, while the isoscalar correlations involve mainly pairing between identical orbitals and spin-orbit partners. In this work we are interested in empirical aspects of the p-n pairing.

Studies of like and unlike nucleon-nucleon pairing from the experimental data or empirical mass formulas may be carried out by computing mass differences (or discrete derivatives). Good indicators of the residual p-n pairing are mass differences of the form[5] (for even-even nuclei)

$$\delta^{pn} = 1/4\ \{2[M(Z,n+1) + M(Z,N-1) + M(Z-1,N) + M(Z+1,N)]$$

$$- [M(Z+1,N+1) + M(Z-1,N+1) + M(Z-1,N-1) + M(Z+1,N-1)]$$

$$-4M(Z,N)\},$$

where M is the (negative) binding energy of the nucleus. We find that these high-order filters, in contrast to simple double binding energy differences, also do a better job of removing A dependence from the systematics. Similar formulas exist for the p-p and n-n pairing gaps.

We are interested in computing the Δ_{pp}, Δ_{nn}, and δ_{pn} mass difference formulas (filters) to understand the origin of proton-neutron pairing both in the experimental data, in empirical mass formulas, and with masses generated from a shell-model application. We have found that one criterion necessary for a filter that describes pairing reasonably is that it includes odd mass neighbors of the nuclei in question.

We find generally that proton-neutron pairing is enhanced for N=Z nuclei as compared to N=Z+2, N=Z+4, ..., nuclei. This enhancement can be seen when computing the Δ_{pp}, Δ_{nn}, and δ_{pn} residual pairing from the experimental masses.[6] We are able to trace the enhancement of pairing to the Wigner term and surface asymmetry terms in general mass formulas. We are also investigating the dependence of this enhancement on the mass number of the system.

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3. JIHIR guest assignee from University of Tennessee, Knoxville.
4. JIHIR guest assignee from Warsaw University, Warsaw, Poland.
5. P. Moller and J. R. Nix, *Nucl. Phys. A* **536**, 20 (1992).
6. H. J. Krappe, J. R. Nix, and A. J. Sierk, *Phys. Rev. C* **20**, 992 (1979).

ABSTRACTS OF PAPERS PUBLISHED OR SUBMITTED FOR PUBLICATION

ASTROPHYSICS

RADIATIVE TRANSFER IN THE COMOVING FRAME[1]

E. Baron,[2] P. H. Hauschildt,[3] A. Mezzacappa

The formulation of the radiative transfer equation in the comoving frame is discussed. For characteristic velocities larger than ~ 2000 km s^{-1}, the effects of advection on the synthetic spectra are non-negligible, and hence they should be included in model calculations. We show that the time-independent or quasi-static approximation is adequate for most astrophysical problems, e.g., hot stars, novae, and supernovae. We examine the use of the Sobolev approximation in modeling moving atmospheres, and find that the number of overlapping lines in the comoving frame makes the approximation suspect in models that predict both lines and continua. We also discuss the form of the Rosseland mean opacity in the comoving frame, and derive a formula that is easy to implement in radiation hydrodynamics calculations.

1. Abstract of published paper: *Mon. Not. R. Astron. Soc.* **278**, 763 (1996).
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3. Arizona State University, Tempe.

NLTE MODELING OF SNe Ia NEAR MAXIMUM LIGHT[1]

E. Baron,[2] P. H. Hauschildt,[3] A. Mezzacappa

Modeling the atmospheres of Sne Ia requires the solution of the NLTE radiative transfer equation. We discuss the formulation of the radiative transfer equation in the comoving frame. For characteristic velocities larger than ~ 2000 km s^{-1}, the effects of advection on the synthetic spectra are non-negligible, and hence should be included in model calculations. We show that the time-independent or quasi-static approximation is adequate for Sne Ia near maximum light, as well as for most other astrophysical problems; e.g., hot stars, novae, and other types of supernovae. We examine the use of the Sobolev approximation in modeling moving atmospheres and find that the number of overlapping lines in the comoving frame makes the approximation suspect in models that predict both lines and continua. We briefly discuss the form of the Rosseland mean opacity in the comoving frame, and present a formula that is easy to implement in radiation hydrodynamics calculations.

1. Abstract of paper to be published in Proceedings of the NATO Advanced Study Institute on Thermonuclear Supernovae,
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3. Arizona State University, Tempe.

DECIPHERING CORE COLLAPSE SUPERNOVAE: IS CONVECTION THE KEY? I. PROMPT CONVECTION[1]

A. Mezzacappa, A. C. Calder,[2] S. W. Bruenn,[3] J. M. Blondin,[4] M. W. Guidry,[5] M. R. Strayer, A. S. Umar[6]

Two-dimensional hydrodynamics is coupled to detailed one-dimensional multigroup flux-limited diffusion neutrino transport to investigate prompt convection in core collapse supernovae. The initial conditions, time-dependent boundary conditions, and neutrino distributions for computing neutrino heating, cooling, and deleptonization rates are obtained from one-dimensional simulations that implement multigroup flux-limited diffusion neutrino transport and one-dimensional hydrodynamics. The development and evolution of prompt convection and its ramifications for the shock dynamics are investigated for both 15 and 25 solar mass models, representative of the two classes of stars with compact and extended iron cores, respectively. In the absence of neutrino transport, prompt convection develops and dissipates on a time scale ~ 15 ms for both models. Prompt convection seeds convection behind the shock, which causes distortions in the shock's sphericity, but on the average, the shock radius is not boosted significantly. In the presence of neutrino transport, prompt convection velocities are too small relative to bulk inflow velocities to result in any significant convective transport of entropy and leptons. A simple analytical model supports the numerical results, indicating that the inclusion of transport reduces the convection growth rates and asymptotic velocities by factors of 4-250.

1. Abstract of paper submitted for publication in *The Astrophysical Journal.*
2. Consultant from Vanderbilt University, Nashville, TN.
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4. North Carolina State University, Raleigh.
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ATOMIC PHYSICS

THE TWO-ELECTRON PROBLEM AND PROSPECTS FOR ATOMIC COLLISION THEORY ON A NUMERICAL LATTICE[1]

D. R. Schultz

An exact numerical treatment of fully correlated two-electron systems is described and placed in context with themes characterizing Chris Bottcher's research regarding time-dependent lattice approaches to the quantum-mechanical solution of atomic collision problems. Tests of the method are summarized in which low-lying bound states are computed and the time dependence of autoionization is described. Finally, prospects for treating the near-threshold electron-impact ionization of hydrogen and photoionization are discussed, as well as the general prospects for further development of this type of lattice treatment.

1. Abstract of published paper: *pp. 167-178 in Atomic Collisions: A Symposium in Honor of Christopher Bottcher (1945-1993), Oak Ridge, TN, March 3-5, 1994*, AIP Conference Proceedings 347, AIP Press, Woodbury, NY, 1995.

THE FULLY CORRELATED TWO-ELECTRON PROBLEM ON A NUMERICAL LATTICE[1]

D. R. Schultz

A technique for solving the time-dependent Schrödinger equation on a numerical lattice is described for the fully correlated two-electron, one-center problem. First applications of the method are briefly summarized here, including the demonstration of its ability to accurately reproduce static solutions for the helium atom, describe the time dependence of the autoionization of a doubly excited state of helium, and to explore the treatment of electron impact of atomic hydrogen.

1. Abstract of published paper: *pp. 42-50 in Proceedings of the Fourth US/Mexico Symposium on Atomic and Molecular Physics, San Juan del Rio, Querétero, Mexico, December 7-10, 1994*, World Scientific Publishing Co., Singapore, 1995.

TIME-DEPENDENT LATTICE APPROACH TO ATOMIC COLLISIONS[1]

D. R. Schultz

Recent progress in developing and applying methods of direct numerical solution of atomic collision problems is described. Various forms of the three-body problem are used to illustrate these techniques. Specifically, the process of ionization in proton, antiproton, and electron impact of atomic hydrogen is considered in applications ranging in computational intensity from collisions simulated in two spatial dimensions to treatment of the three-dimensional, fully correlated two-electron Schrödinger equation. These examples demonstrate the utility and feasibility of treating strongly interacting atomic systems through time-dependent lattice approaches.

1. Abstract of published paper: *pp. 455-470 in Proceedings of XIX International Conference on the Physics of Electronic and Atomic Collisions, Whistler, Canada, July-August, 1995*, AIP Conference Proceedings 360, AIP Press, Woodbury, NY, 1995.

DIRECT SOLUTION OF THE TIME-DEPENDENT SCHRÖDINGER EQUATION FOR PROTON-HYDROGEN COLLISIONS IN TWO-DIMENSIONAL CARTESIAN SPACE[1]

P. Gavras,[2] M. S. Pindzola,[2] D. R. Schultz, J. C. Wells[3]

The wave function for the collision of a proton with a hydrogen atom is obtained by direct solution of the time-dependent Schrödinger equation in a model two-dimensional Cartesian space using lattice techniques. The dimensional reduction from the full three-dimensional (3D) space allows the consideration of huge collision "volumes" with minimal computational expense while still preserving the idea of an impact parameter. The probabilities for charge exchange and ionization are estimated for different projectile energies ranging from 10 to 100 keV/amu. Comparisons with full 3D calculations in smaller collision volumes show that the time-dependent behavior of the probability densities is quite similar for the 2D soft core model interaction chosen here. The ionization dynamics are further analyzed in regard to the fate of that fraction of the probability density located near the saddle point between projectile and target potentials.

1. Abstract of published paper: *Phys. Rev. A* **52**, 3868 (1995).
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ENERGY AND ANGULAR DISTRIBUTIONS OF ELECTRONS FROM ION IMPACT ON ATOMIC AND MOLECULAR HYDROGEN. II. 20-114 keV H^+ + H (Ref. 1)

G. W. Kerby III,[2] M. W. Gealy,[2] Y.-Y. Hsu,[2] M. E. Rudd,[2] D. R. Schultz, C. O. Reinhold

Results of crossed-beam measurements of cross sections differential in ejected-electron energy and angle for ionization of atomic hydrogen by 20-114 keV protons are reported. Secondary electrons were measured over an energy range of 1.5-300 eV and an angular range of 15°-165°. Atomic hydrogen targets were produced in a radio-frequency discharge source with a dissociation fraction of about 74%. Ratios of cross sections for H targets to those for H_2 targets were obtained from measurements on the mixed target. From these ratios, the measured dissociation fractions, and the absolute cross sections measured for H_2 targets, the cross sections for H targets were determined. These measurements are compared with the results of the first-order Born approximation, the continuum distorted-wave eikonal initial-state approximation, and the classical trajectory Monte Carlo (CTMC) methods. Good overall agreement is found with the CTMC results, except for slow, backward electron emission. The addition of the classically suppressed dipole transitions from the Born approximation to the CTMC results yields a good estimate of the ejected-electron spectrum.

1. Abstract of published paper: *Phys. Rev. A* **51**, 2256 (1995).
2. University of Nebraska, Lincoln.

ENERGY AND ANGULAR DISTRIBUTIONS OF ELECTRONS FROM ION IMPACT ON ATOMIC AND MOLECULAR HYDROGEN. IV. 28-114 keV He^+ + H COLLISIONS[1]

Y.-Y. Hsu,[2] M. W. Gealy,[2] G. W. Kerby III,[2] M. E. Rudd,[2] D. R. Schultz, C. O. Reinhold

Absolute ionization cross sections for 28-114 keV helium ion impact on atomic hydrogen, differential in energy and angle of the ejected electrons, have been obtained from crossed-beam measurements and previously measured cross sections for molecular hydrogen targets. A radio-frequency discharge source produced a mixed atomic and molecular target with a typical dissociation fraction of 74%. Energy spectra were measured from 1.5 to 130 eV by an electrostatic analyzer with a resolution of 5%. The angular range was 15°-160°. Results are compared with calculations based on the first Born, continuum distorted-wave eikonal initial state, and classical trajectory Monte Carlo methods. Total electron yields are obtained by combining calculations that are separately performed for liberating the target and projectile electrons. Model potentials are used to represent the interparticle separation-dependent screening of the nuclear charges experienced by the electrons. Though projectile electron emission is a negligible component of the total ionization cross section for the present collision energies, its contribution is significant for particular regions of the spectrum of ejected electrons. Through comparison with our proton-impact data [Kerby et al., Phys. Rev. A **51**, 2256 (1995)], differences and similarities are demonstrated owing to the common asymptotic charge of these two projectiles but different nuclear charges and the electron carried by the He^+ ion. Comparisons are also made illustrating the differences between atomic and molecular hydrogen targets.

1. Abstract of published paper: *Phys. Rev. A* **53**, 303 (1996).
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INELASTIC PROCESSES IN SLOW COLLISIONS OF ANTIPROTONS WITH HYDROGENIC IONS[1]

P. S. Krstic,[2] D. R. Schultz, R. K. Janev[3]

A comprehensive theoretical study is presented of the physical processes which govern inelastic transitions in slow collisions of antiprotons with hydrogenic ions. Two-center one-electron mechanisms are highlighted. Various channels for ionization and excitation are identified utilizing the theory of hidden crossings. New features of the quasimolecular potentials, caused by the negative charge of the antiproton, are described in detail, with particular attention to the topology of the electronic eigenenergy surface in the plane of complex internuclear distance. The ionization and excitation cross sections are calculated and compared with the results of other theories and recent experiments.

1. Abstract of published paper: *J. Phys. B: At. Mol. Opt. Phys.* **29**, 1941 (1996).
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TIME-DEPENDENT CLOSE-COUPLING METHOD FOR ELECTRON-IMPACT IONIZATION OF HYDROGEN[1]

M. S. Pindzola[2] and D. R. Schultz

Electron-impact ionization of atomic hydrogen is studied by direct solution of a set of time-dependent close-coupled partial differential equations. The close-coupled equations describe the propagation of a time-evolving wave packet on a two-dimensional radial lattice. Following the collision, the wave packet is projected onto stationary states of the target to obtain probabilities for elastic and inelastic scattering processes. Ionization cross sections are calculated for various LS partial waves and compared with previous theoretical methods.

1. Abstract of published paper: *Phys. Rev. A* **53**, 1525 (1996).
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IONIZATION OF HYDROGEN AND HYDROGENIC IONS BY ANTIPROTONS[1]

D. R. Schultz, P. S. Krstic,[2] C. O. Reinhold, J. C. Wells[3]

Presented here is a description of the ionization of hydrogen and hydrogenic ions by antiproton impact, based on very large-scale numerical solutions of the time-dependent Schrödinger equation in three spatial dimensions and on analysis of the topology of the electronic eigenenergy surfaces in the plane of complex internuclear distance. Comparison is made with other theories and very recent measurements.

1. Abstract of published paper: *Phys. Rev. Lett.* **76**, 2882 (1996).
2. ORISE Postdoctoral Research Associate.
3. Consultant from Harvard-Smithsonian Center for Astrophysics, Cambridge, MA.

NUMERICAL SOLUTION OF THE TIME-DEPENDENT SCHRÖDINGER EQUATION FOR INTERMEDIATE-ENERGY COLLISIONS OF ANTIPROTONS WITH HYDROGEN[1]

J. C. Wells,[2] D. R. Schultz, P. Gavras,[3] M. S. Pindzola[3]

Studied is the behavior of ionization in intermediate-energy collisions of antiprotons with atomic hydrogen by direct solution of the time-dependent Schrödinger equation represented on a three-dimensional Cartesian lattice. Total cross sections for these processes are computed over the collision energy range of 0.2 to 500 keV from knowledge of the asymptotic state probabilities as a function of impact parameter. The computed ionization cross sections are in good agreement with results from recent experiments conducted at CERN [Phys. Rev. Lett. **74**, 4627 (1995)]. In the energy range from 0.2 to 30 keV, for which measurements are not available, our calculations are in qualitative agreement with other results based on classical-trajectory and coupled-channel methods, confirming the predicted significant difference from the analog proton-impact ionization process. This contrast with proton-hydrogen collisions is also explored qualitatively by employing a model two-dimensional space in which lattice solutions are less computationally intensive.

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1. Abstract of published paper: *Phys. Rev. A* **54**, 593 (1996).
2. Consultant from Harvard-Smithsonian Center for Astrophysics, Cambridge, MA.
3. Auburn University, Auburn, AL.

TWO-CENTER EFFECTS IN THE EJECTED-ELECTRON SPECTRA IN ION-ATOM COLLISIONS[1]

D. R. Schultz, C. O. Reinhold, R. E. Olson[2]

Features of the spectra of electrons ejected in ion-atom collisions which arise due to "two-center" effects are described. After a brief survey of these effects, they are illustrated in more detail through examples of studies involving intermediate-energy collisions.

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1. Abstract of published paper: *pp. 84-102 in Two-Center Effects in Ion-Atom Collisions* (Proceedings of Symposium in Honor of M. Eugene Rudd, Lincoln, Nebraska, May 13-14, 1994) AIP Conference Proceedings 362, AIP Press, Woodbury, NY, 1996.
2. University of Missouri, Rolla.

ELECTRON-ENERGY AND ANGULAR-DISTRIBUTION THEORY FOR LOW-ENERGY ION-ATOM COLLISIONS[1]

S. Y. Ovchinnikov[2] and J. H. Macek[3]

Presented are the first *ab initio* calculations of electron energy and angular distributions of saddle-point and S-promotion electrons for ionization in proton-hydrogen atom collisions. The calculations are based on outgoing wave Sturmian expansions in the frequency domain. They go beyond the usual Born-Oppenheimer separation of electron and nuclei motion, and display the "v/2" peaks and the continuum capture cusps missing in previous theories.

1. Abstract of published paper: *Phys. Rev. Lett.* **75**, 2474 (1995).
2. Guest assignee from University of Tennessee, Knoxville.
3. UT-ORNL Distinguished Scientist.

HIDDEN-CROSSING THEORY OF THRESHOLD IONIZATION OF ATOMS BY ELECTRON IMPACT[1]

J. H. Macek,[2] S. Y. Ovchinnikov,[3] S. V. Pasovets[4]

The hidden-crossing theory, familiar in the context of ion-atom collisions, is adapted to the computation of ionization cross sections and spin asymmetries for electron impact on atomic hydrogen. Computed ionization cross sections and spin asymmetry agree within 10% with measurements. A rapid variation of the spin asymmetry near threshold is found, and its origin is traced to anharmonic corrections to the Wannier threshold law for triplet spin states.

1. Abstract of published paper: *Phys. Rev. Lett.* **74**, 4631 (1995).
2. UT-ORNL Distinguished Scientist.
3. Guest assignee from University of Tennessee, Knoxville.
4. A. F. Ioffe Physical Technical Institute, St. Petersburg, Russia.

SADDLE-POINT ELECTRONS AND HIDDEN CROSSINGS[1]

M. Pieksma[2] and S. Y. Ovchinnikov[3]

Diabatic transitions in slow atomic collisions can, in the case of a three-body Coulomb system, very effectively and elegantly be described by so-called hidden crossings. For example, the H^+ - H system does not show the well-known Landau-Zener-type avoided crossings, in which case the application of the theory of hidden crossings becomes very useful. One type of such hidden crossings is connected with the phenomenon of saddle-point ionization. Saddle-point electrons, hidden crossings, and their interconnection are discussed.

1. Abstract of published paper: *Comments At. Mol. Phys.* **31**, 21 (1995).
2. Utrecht University, Utrecht, The Netherlands.
3. Guest assignee from University of Tennessee, Knoxville.

DIRECT IONIZATION IN THE QUASIMOLECULE H-He (Ref. 1)

G. N. Ogurtsov,[2] A. G. Kroupyshe,[2] M. G. Sargsyan,[2] Y. S. Gordeev,[2] S. Y. Ovchinnikov[3]

Doubly differential cross sections for electron ejection in H-He collisions have been measured in the incident atom energy range 2.3-10 keV. Analysis of the experimental data, on the basis of the adiabatic theory of direct ionization, has been made. Parameters of the quasimolecule, namely, the energy of the initial $2p\sigma$ state, coupled with the continuum, the effective charge, and the real and imaginary parts of the internuclear distance at which the "superpromoted" diabatic term crosses the boundary of continuum, have been determined. The values of the initial-state energy and the effective charge agree well with the corresponding parameters of the Li-united atom, whereas the dynamical characteristics ReR(E) and ImR(E) reveal considerable influence of electron correlations. The possibility for the development of an alternative method of quantitative spectroscopy of quasimolecules, based on the analysis of experimental data on differential cross sections for direct ionization, is discussed.

1. Abstract of published paper: *Phys. Rev. A* **53**, 2391 (1996).
2. A. F. Ioffe Physical Technical Institute, St. Petersburg, Russia.
3. Guest assignee from University of Tennessee, Knoxville.

STRONG INDUCED-DIPOLE FIELD OSCILLATIONS OF THE dtμ SYSTEM ABOVE THE tμ(n=2) THRESHOLD[1]

K. Hino[2] *and J. H. Macek*[3]

Elastic, inelastic, and muon transfer processes of the dtμ system above the tμ(n=2) threshold are studied theoretically using the hyperspherical coordinate method. Pronounced oscillations in the cross sections for these processes, due to strong, attractive dipole potentials in this system, are found. In addition to the expected Gailitis-Damburg Stark mixing oscillations, unexpected oscillations due to diabatic couplings of channels lacking attractive dipole potentials with those that have them are evident. The two types of oscillations interfere to produce the structure that appears in the computed cross sections.

1. Abstract of paper to be published in *Physical Review Letters*.
2. University of Electro-Communications, Tokyo, Japan.
3. UT-ORNL Distinguished Scientist.

THRESHOLD LAW FOR IONIZATION CROSS SECTIONS IN THE TEMKIN-POET MODEL[1]

J. H. Macek[2] *and W. Ihra*[3]

An integral representation of wave functions for the Temkin-Poet model of electron impact on atomic hydrogen is given. Approximate wave functions are evaluated analytically for large hyper-radius to extract the ionization S-matrix element. An ionization cross section of the form $\exp[-aE^{-1/6} + bE^{1/6}]$, where a and b are positive constants, is derived. The exponential suppression of ionization for small E appears to be the quantum counterpart of the delayed onset of ionization in the classical theory for this model.

1. Abstract of paper submitted for publication in *Physical Review A*.
2. UT-ORNL Distinguished Scientist.
3. University of London, Surrey, England.

INTERFERENCE OSCILLATIONS IN IONIZATION OF EXTREME STARK STATES BY HALF-CYCLE PULSES[1]

C. O. Reinhold and J. Burgdörfer[2]

The classical, semiclassical, and quantum dynamics of parabolic Rydberg states of hydrogen, subject to half-cycle electromagnetic pulses as a function of the field strength and the duration of the pulses is studied. It is shown that for the most "red-shifted" Stark state the quantum ionization probability oscillates around the classical value. These oscillations can be described semiclassically in terms of path interference. By

contrast, the ionization probability of the extreme "blue-shifted" state is a smooth function of field strength. These predictions could be tested experimentally.

1. Abstract of published paper: *Phys. Rev. A* **51**, 3410 (1995).
2. Adjunct staff member from University of Tennessee, Knoxville.

ESCAPE PROBABILITIES FOR ELECTRONS EMITTED DURING THE INTERACTION OF SLOW, HIGHLY CHARGED IONS WITH METAL SURFACES[1]

C. Lemell,[2] H. P. Winter,[2] F. Aumayr,[2] J. Burgdörfer,[3] C. Reinhold

During the interaction of slow ($v << 1$ a.u.) highly charged ions with metal surfaces, a large number of electrons is emitted, only a fraction of which escapes into vacuum and is accessible to measurements. In order to correlate experimentally determined yields with recently developed models which provide the total number of electrons released by the projectile-solid interaction, we have calculated escape fractions for electrons released near the surface. Results are presented for electrons emitted in autoionization processes above the metal surface as well as emitted via "peeling off" upon surface impact.

1. Abstract of published paper: *Nucl. Instrum. Methods Phys. Res. B* **102**, 33 (1995).
2. Technical University of Vienna, Vienna, Austria.
3. Adjunct staff member from University of Tennessee, Knoxville.

SCALED-TIME DYNAMICS OF IONIZATION OF RYDBERG STARK STATES BY HALF-CYCLE PULSES[1]

C. O. Reinhold, J. Burgdörfer,[2] R. R. Jones,[3] C. Raman,[4] P. H. Bucksbaum[4]

Studied is the time dependence of the ionization of Stark Rydberg states of hydrogen subject to half-cycle electromagnetic pulses. It is found that the quantum ionization probability for the most "blue-shifted" Stark state exhibits a purely classical oscillating pattern as a function of time whose frequency is associated with the perturbed orbital frequency of the electron. It is shown that these oscillations could be observed experimentally when a scaled-time analysis of ionization data for hydrogen is employed. The calculations are compared with experimental data for sodium.

1. Abstract of published paper: *J. Phys. B* **28**, L457 (1995).
2. Adjunct staff member from University of Tennessee, Knoxville.
3. University of Virginia, Charlottesville.
4. University of Michigan, Ann Arbor.

EVOLUTION OF RYDBERG STATES IN HALF-CYCLE PULSES: CLASSICAL, SEMICLASSICAL, AND QUANTUM DYNAMICS[1]

J. Burgdörfer[2] and C. O. Reinhold

Summarized are recent theoretical advances in the description of the evolution of Rydberg atoms subject to ultrashort pulses extending only a fraction of an optical cycle. Classical, semiclassical, and full quantum calculations have been performed in order to delineate the classical quantum correspondence for impulsively perturbed atomic systems. Observed were classical and quantum (or semiclassical) oscillations in excitation and ionization which depend on the initial state of atoms and on the strength of the perturbation. These predictions can be experimentally tested.

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1. Abstract of paper to be published in *Proceedings of 4th International Workshop on Classical Quantum Correspondence, Philadelphia, PA.*
2. Adjunct staff member from University of Tennessee, Knoxville.

SIMULATION OF EXCITED-STATE FORMATION OF HYDROGEN IN TRANSMISSION OF RELATIVISTIC H^- IONS THROUGH THIN FOILS[1]

B. Gervais,[2] C. O. Reinhold, J. Burgdörfer[3]

A theoretical description is presented of the formation of excited states H(n) due to the interaction of relativistic H^- ions with thin foils. The classical transport theory based on a Monte Carlo solution of a Langevin equation is generalized to relativistic speeds of the projectile. Relativistic corrections are introduced to both collision dynamics and kinematics. The n distribution of excited states, H(n), is studied as a function of the foil thickness and compared with recent experimental data.

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1. Abstract of published paper: *Phys. Rev. A* **53**, 3189 (1996).
2. National Center for Scientific Research, Caen, France.
3. Adjunct staff member from University of Tennessee, Knoxville.

INTERACTION OF HIGHLY CHARGED IONS WITH SURFACES[1]

J. Burgdörfer,[2] C. O. Reinhold, L. Hägg,[3] F. W. Meyer

An overview is given of recent advances in the theoretical description of the interaction of multiply charged ions with surfaces. Simulations are presented displaying the formation of hollow atoms when slow, highly charged ions approach the surface. It is shown that above-surface neutralization proceeds via hollow-atom formation. Relaxation of the multiply excited states to the ground state occurs only subsequent to the close encounter with the topmost atomic layer.

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1. Abstract of published paper: *Aust. J. Phys.* **49**, 527 (1996).
2. Adjunct staff member from University of Tennessee, Knoxville.
3. Stockholm University, Stockholm, Sweden.

IONIZATION OF VERY HIGH-n RYDBERG ATOMS BY HALF-CYCLE PULSES IN THE SHORT-PULSE REGIME[1]

M. T. Frey,[2] F. B. Dunning,[2] C. O. Reinhold, J. Burgdörfer[3]

The ionization of potassium Rydberg atoms with n ~ 388 and n ~ 520 by pulsed electric fields, whose durations which range from ~ 2 ns to ~ 110 ns span the transition from the short-pulse to the long-pulse regime, is investigated experimentally and the data compared with the results of classical trajectory Monte Carlo (CTMC) calculations. Excellent agreement is observed between theory and experiment, providing a benchmark test for the validity of the classical limit of ionization. Very high-n atoms provide an excellent tool with which to probe the response of atoms to pulsed electric fields in the short-pulse regime.

1. Abstract of published paper: *Phys. Rev. A* **53**, R2929 (1996).
2. Rice University, Houston, TX.
3. Adjunct staff member from University of Tennessee, Knoxville.

DYNAMICS OF RYDBERG WAVEPACKETS GENERATED BY HALF-CYCLE PULSES[1]

C. O. Reinhold, J. Burgdörfer,[2] M. T. Frey,[3] F. B. Dunning[3]

Wavepackets comprising a superposition of very high-lying Rydberg states have been created using a half-cycle pulse (HCP). The properties of the wavepacket are probed using a second HCP that is applied following a variable time delay. The second pulse ionizes a fraction of the atoms, and the survival probability exhibits pronounced oscillations that are associated with the quasi-periodic evolution of the wavepacket. Good agreement is found between the experimental data and the results of a classical trajectory Monte Carlo simulation demonstrating that, for the times investigated, classical quantum correspondence holds, and quantum corrections are negligible.

1. Abstract of published paper: *Phys. Rev. A* **54**, R33 (1996).
2. Adjunct staff member from University of Tennessee, Knoxville.
3. Rice University, Houston, TX.

THEORETICAL DESCRIPTION OF FAST KINETIC ELECTRON EMISSION IN ION-SURFACE COLLISIONS[1]

C. O. Reinhold and J. Burgdörfer[2]

A microscopic description is presented of the emission of fast electrons in glancing-angle ion-surface collisions. A classical trajectory Monte Carlo approach is employed which treats the primary production of kinetic electrons in close collisions and their subsequent transport through the surface region on the same footing. Dynamic image interactions and multiple scattering are explicitly included. As an application, the ejected-electron spectra are analyzed over a broad range of electron energies and emission angles for 0.2-0.5 MeV/u Li ions interacting with SnTe(001) surfaces. Good agreement is found with experiment for the shape of the spectrum of forward-ejected electrons containing prominent structures such as the convoy electron peak and the binary ridge.

1. Abstract of paper to be published in *Physical Review A*.
2. Adjunct staff member from University of Tennessee, Knoxville.

TRANSPORT OF FAST ELECTRONS NEAR SURFACES[1]

C. O. Reinhold, J. Burgdörfer,[2] K. Kimura,[3] M. Mannami[3]

A microscopic model has been developed to study emission of fast electrons in glancing-angle ion-surface collisions using a classical trajectory Monte Carlo approach. The model accounts for dynamic image interactions and multiple scattering near the surface. It is shown that a sizable fraction of the convoy peak is produced by ionization of electrons transiently bound to the impinging ion. Properties of the collision kernels near the surface are discussed. Good agreement is found with recent coincidence experiments for 0.2-0.5 MeV/u Li ions interacting with SnTe(001) surfaces.

1. Abstract of published paper: *Proceedings of 16th International Conference on Atomic Collisions in Solids*, Linz, Austria, July 17-21, 1995 (*Nucl. Instrum. Methods Phys. Res. B* **115**, 233 (1996)).
2. Adjunct staff member from University of Tennessee, Knoxville.
3. Kyoto University, Kyoto, Japan.

SOLID-STATE EFFECTS IN ELECTRON EMISSION FROM ATOMIC COLLISIONS NEAR SURFACES[1]

C. O. Reinhold, J. Burgdörfer,[2] R. Minniti,[3] S. B. Elston[2]

A brief progress report is presented of recent studies of the ejected-electron spectra arising from glancing-angle ion-surface scattering involving collision energies of hundreds of keV/u. A broad range of electron energies and emission angles is analyzed containing prominent structures such as the convoy electron peak and the binary ridge. Particular emphasis is placed on the search for signatures of dynamic image interactions and multiple scattering near surfaces.

1. Abstract of paper to be published in *Proceedings of 6th Workshop on Fast Ion-Atom Collisions*, Debrecen, Hungary, September 4-6, 1996 (*Nuclear Instruments and Methods in Physics Research B*).
2. Adjunct staff member from University of Tennessee, Knoxville.
3. Guest assignee from University of Tennessee, Knoxville.

VERY HIGH-n STARK WAVEPACKETS GENERATED BY AN ELECTRIC FIELD STEP (Ref. 1)

M. T. Frey,[2] F. B. Dunning,[2] C. O. Reinhold, J. Burgdörfer[3]

Wavepackets comprising a coherent superposition of n $\cong$ 390 Stark states have been created in potassium by rapid application of a DC field. Their properties are examined using a half-cycle probe pulse that is applied following a variable time delay and which ionizes a fraction of the excited atoms. The survival probability exhibits pronounced oscillations (quantum beats) that are associated with the time evolution of the wavepacket. Interestingly, even in the present regime of complete overlap of different Stark manifolds, a single dominant beat frequency is observed, and this is explained quantum mechanically in terms of energy level statistics. Similar behavior is predicted by classical trajectory Monte Carlo simulations which reproduce well the experimental observations demonstrating classical quantum correspondence in high-n systems.

1. Abstract of paper submitted for publication in *Physical Review A*.
2. Rice University, Houston, TX.
3. Adjunct staff member from University of Tennessee, Knoxville.

ENERGY GAIN OF HIGHLY CHARGED IONS IN FRONT OF LiF (Ref. 1)

L. Hägg,[2] C. O. Reinhold, J. Burgdörfer[3]

Estimates are presented of the energy gain of highly charged ions approaching a LiF surface, based on a modified classical over-barrier model for insulators. The analysis includes the energy gain by image acceleration, as well as the deceleration due to charge-up of the surface in a staircase sequence. The role of

the frequency-dependent dielectric response of LiF is emphasized. The resulting velocity-dependent total energy gain is studied in detail, and the results are compared with experimental data.

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1. Abstract of paper to be published in *Proceedings of 11th International Workshop on Inelastic Ion-Surface Collisions,* Wangerooge, Germany, September 22-27, 1996 (*Nuclear Instruments & Methods B*).
2. Stockholm University, Stockholm, Sweden.
3. Adjunct staff member from University of Tennessee, Knoxville.

ABOVE-SURFACE NEUTRALIZATION OF SLOW, HIGHLY CHARGED IONS IN FRONT OF IONIC CRYSTALS[1]

L. Hägg,[2] C. O. Reinhold, J. Burgdörfer[3]

A theoretical analysis is presented of the above-surface neutralization of highly charged ions in front of LiF. The study is based on the assumption that the dominant electron transfer occurs in the classically allowed region. Estimates of critical distances and corresponding quantum numbers for capture from an ionic crystal within the classical over-barrier (COB) model are presented, which differ considerably from corresponding results for metals. The role of the dielectric response of LiF is investigated. In addition, classical trajectory simulations are performed for the first time for a slow, highly charged ion approaching an insulator. It is shown that capture effectively begins ~ 3 a.u. closer to the surface than estimated from the COB model. This correction can be incorporated into a modified COB model. The energy gain for grazing incidence ions is obtained using a staircase model which includes the deceleration due to charge-up of the surface.

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1. Abstract of paper submitted for publication in *Physical Review A*.
2. Stockholm University, Stockholm, Sweden.
3. Adjunct staff member from University of Tennessee, Knoxville.

ATOMIC RESONANCES OF HYDROGEN NEAR ALUMINUM SURFACES: ADIABATIC EVOLUTION OF THE GROUND STATE[1]

S. A. Deutscher,[2] X. Yang,[2] J. Burgdörfer[3]

Complex adiabatic potential curves are an essential input to atomic surface scattering calculations employing the coupled-states method. New calculations for the ground state of hydrogen near a jellium surface with the density of aluminum are presented. Two complementary techniques have been implemented: the complex rotation method and the stabilization method. Large-scale matrix diagonalization and realistic effective single-particle potentials are employed. The influence of the surface potential on the features of the resonances, as well as the adiabatic evolution of the wave function and the resonance parameters as a function of the distance d from the surface, have been investigated. Application to the ground state H(1s) yields significant differences for the position and width of the resonance compared to previously available data. Implications for electronic transitions in atom-surface collisions are discussed. The applicability of semiclassical theory for resonance parameters is tested and the role of over-barrier transitions is highlighted.

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1. Abstract of paper to be published in *Physical Review A*.
2. University of Tennessee, Knoxville.
3. Adjunct staff member from University of Tennessee, Knoxville.

NUCLEAR PHYSICS

GENERATOR-COORDINATE METHOD STUDY OF HEXADECAPOLE CORRELATIONS IN SUPERDEFORMED ^{194}Hg (Ref. 1)

P. Magierski,[2] *P.-H. Heenen,*[3] *W. Nazarewicz*[4]

The role of hexadecapole correlations in the lowest superdeformed band of ^{194}Hg is studied by self-consistent mean-field methods. The generator-coordinate method with particle number projection has been applied using Hartree-Fock wave functions defined along three different hexadecapole paths. In all cases, the ground state is not significantly affected by hexadecapole correlations and the energies of the corresponding first-excited hexadecapole vibrational states lie high in energy. The effect of rotation is investigated with the Skyrme-Hartree-Fock-Bogoliubov method and a zero range density-dependent pairing interaction.

1. Abstract of published paper: *Phys. Rev. C* **51**, 2880 (1995).
2. Warsaw University of Technology, Warsaw, Poland.
3. Université Libre de Bruxelles, Brussels, Belgium.
4. JIHIR guest assignee from University of Tennessee, Knoxville.

OCTUPOLE DEFORMATION IN ^{142,143}Ba AND ^{144}Ce: NEW BAND STRUCTURES IN NEUTRON-RICH Ba ISOTOPES[1]

S. J. Zhu,[2] *Q. H. Lu,*[3] *J. H. Hamilton,*[3] *A. V. Ramayya,*[3] *L. K. Peker,*[3] *M. G. Wang,*[2] *W. C. Ma,*[3] *B.R.S. Babu,*[3] *T. N. Ginter,*[3] *J. Kormicki,*[4] *D. Shi,*[3] *J. K. Deng,*[3] *W. Nazarewicz,*[5] *J. O. Rasmussen,*[6] *M. A. Stoyer,*[6] *S. Y. Chu,*[6] *K. E. Gregorich,*[6] *M. F. Mohar,*[6] *S. Asztalos,*[6] *S. G. Prussin,*[7] *J. D. Cole,*[8] *R. Aryaeinejad,*[8] *Y. K. Dardenne,*[8] *M. Drigert,*[8] *K. J. Moody,*[9] *R. W. Loughed,*[9] *J. F. Wild,*[9] *N. R. Johnson,*[10] *I. Y. Lee,*[6] *F. K. McGowan,*[11] *G. M. Ter-Akopian,*[12] *Yu. Ts. Oganessian*[12]

New, high-spin band structures are established for the neutron-rich nuclei ^{142,143,145,147}Ba and ^{144}Ce, and levels of ^{144,146}Ba extended to higher spins from the study of γ-γ and γ-γ-γ coincidence studies in spontaneous fission. Alternating parity sequences connected by strong electric dipole transitions are identified in ^{142,143}Ba and ^{144}Ce, but not in ^{145,147}Ba, to confirm theoretical predictions of stable octupole deformation for N = 86.

1. Abstract of published paper: *Phys. Lett. B* **357**, 273 (1995).
2. Tsinghua University, Beijing, P.R.C.
3. Vanderbilt University, Nashville, TN.
4. UNISOR, Oak Ridge Institute for Science and Education, Oak Ridge, TN.
5. JIHIR guest assignee from University of Tennessee, Knoxville.
6. Lawrence Berkeley Laboratory, Berkeley, CA.
7. University of California, Berkeley.
8. Idaho National Engineering Laboratory, Idaho Falls, ID.
9. Lawrence Livermore National Laboratory, Livermore, CA.
10. Guest assignee.
11. ORNL retiree.
12. Joint Institute for Nuclear Research, Dubna, Russia.

OBSERVATION OF SUPERDEFORMATION IN ^{82}Sr (Ref. 1)

A. G. Smith,[2] P. J. Dagnall,[2] J. C. Lisle,[2] D. H. Smalley,[2] T. R. Werner,[3] R. Chapman,[4] C. Finck,[5] B. Haas,[5] M. Leddy,[2] W. Nazarewicz,[6] D. Prévost,[5] N. Rowley,[2] H. Savajols[5]

The EUROGAM Phase 2 array has been used to detect γ rays following the reaction of ^{30}Si on ^{58}Ni at 134 MeV. Two rotational cascades exhibiting characteristic superdeformed behavior have been observed in ^{82}Sr. Cranked Woods-Saxon calculations have been performed and these suggest that both bands have the $\nu5^2\pi5^1$ intrinsic intruder configuration and that they differ in the signature component of the [431]1/2 proton orbital which is occupied.

1. Abstract of published paper: *Phys. Lett. B* **355**, 32 (1995).
2. University of Manchester, Manchester, England.
3. Warsaw University, Warsaw, Poland.
4. University of Paisley, Paisley, Scotland.
5. Centre de Recherches Nucléaires, Strasbourg Cedex, France.
6. JIHIR guest assignee from University of Tennessee, Knoxville.

MULTICLUSTERING AND PHYSICS OF EXOTIC NUCLEAR SHAPES[1]

W. Nazarewicz,[2] S. Cwiok,[3] J. Dobaczewski,[4] J. X. Saladin[5]

The importance of the ground-state shell structure for the formation and stability of excited exotic nuclear configurations is discussed in terms of the multicluster model, based on dynamical symmetries of a three-dimensional harmonic oscillator. As a spectacular example, it is shown that the density distribution at the third hyperdeformed minimum in the actinide nuclei resembles a di-nucleus consisting of a nearly spherical fragment around the doubly magic ^{132}Sn, and a well-deformed fragment from the neutron-rich A~100 region.

1. Abstract of published paper: *Acta Physica Polonica B* **26**, 291 (1995) (Proceedings, XXIX Zakopane School of Physics, Zakopane, Poland, September 5-14, 1994).
2. JIHIR guest assignee from University of Tennessee, Knoxville.
3. JIHIR guest assignee from Warsaw University of Technology, Warsaw, Poland.
4. Warsaw University, Warsaw, Poland.
5. University of Pittsburgh, Pittsburgh, PA.

CLOSED SHELLS AT DRIP-LINE NUCLEI[1]

J. Dobaczewski,[2] W. Nazarewicz,[3] T. R. Werner[2]

The shell structure of magic nuclei far from stability is discussed in terms of the self-consistent spherical Hartree-Fock-Bogoliubov theory. In particular, the sensitivity of the shell-gap sizes and the two-neutron separation energies to the choice of particle-hole and particle-particle components of the effective interaction is investigated.

1. Abstract of published paper: *Physica Scripta T* **56**, 15 (1995).
2. JIHIR guest assignee from Warsaw University, Warsaw, Poland.
3. JIHIR guest assignee from University of Tennessee, Knoxville.

LIMITS OF PROTON STABILITY NEAR ^{100}Sn (Ref. 1)

J. Dobaczewski[2] *and W. Nazarewicz*[3]

The two-proton stability in even-even nuclei around the doubly magic ^{100}Sn is examined by the self-consistent Skyrme-Hartree-Fock-Bogoliubov theory. According to analysis, the nuclei ^{98}Sn and ^{106}Te are stable to two-proton decay, while ^{96}Sn and ^{104}Te lie beyond the two-proton drip line.

1. Abstract of published paper: *Phys. Rev. C* **51**, 1070 (1995).
2. JIHIR guest assignee from Warsaw University, Warsaw, Poland.
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PHYSICS OF EXOTIC NUCLEAR STATES[1]

W. Nazarewicz,[2] *J. Dobaczewski,*[3] *T. R. Werner*[3]

The nature of exotic nuclei with extreme isospin values is one of the most exciting challenges today, both experimentally and theoretically. The coupling between bound states and the particle continuum invites strong interplay between various aspects of nuclear structure and reaction theory. Perspectives for new physics far from stability are discussed.

1. Abstract of published paper: *Physica Scripta T* **56**, 9 (1995).
2. JIHIR guest assignee from University of Tennessee, Knoxville.
3. JIHIR guest assignee from Warsaw University, Warsaw, Poland.

PHYSICS OF DRIP-LINE NUCLEI[1]

T. R. Werner,[2] *J. Dobaczewski,*[2] *W. Nazarewicz*[3]

The nature of exotic nuclei with extreme isospin values is analyzed within various models, with special emphasis on the role of coupling between bound states and the particle continuum. Applicability of the shell-correction method of nuclei far from the beta stability line is discussed. In particular, the sensitivity of predicted locations of one- and two-particle drip lines to details of the macroscopic-microscopic model is analyzed. Hartree-Fock and Hartree-Fock-Bogoliubov theories with different parametrizations are used to calculate the properties of exotic nuclei (masses, deformations, radii, and single-particle properties). The results are compared with available experimental data, and their dependence on the models used is discussed.

1. Abstract of published paper: *Rev. Mex. Fis.* **41**, 1 (1995) (Proceedings, XVIII Nuclear Physics Symposium, Oaxtepec, Mexico, January 4-7, 1995).
2. JIHIR guest assignee from Warsaw University, Warsaw, Poland
3. JIHIR guest assignee from University of Tennessee, Knoxville.

THE OBSERVATION OF SUPERDEFORMED STRUCTURE IN MASS-80 NUCLEI[1]

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The reaction of ^{30}Si on ^{58}Ni at 134 MeV was used to populate ^{82}Sr and ^{82}Y. The experiment was performed at the C.R.N. Laboratory in Strasbourg, where the EUROGAM Phase 2 array was used to detect coincident γ rays. Three high-spin rotational cascades have been observed, two signature partner bands in ^{82}Sr and one band in ^{82}Y. All three bands exhibit characteristic superdeformed behavior. The bands have been interpreted as superdeformed bands built upon the [431]1/2 orbital with a $\pi 5^1 \nu 5^2$ intrinsic intruder configuration.

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1. Abstract of published paper: *Acta. Phys. Pol. B* **27**, 155 (1996).
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COLLECTIVE HIGH-SPIN STATES IN THE LIGHT ODD $f_{7/2}$ NUCLEI[1]

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The high-spin states in ^{45}Sc, ^{45}Ti, and ^{43}Ca were studied with the GASP multidetector array coupled with the recoil mass spectrometer in Legnaro. The nuclei were excited in the ^{30}Si + 60 MeV ^{18}O reaction. Lifetimes were extracted from the analysis of the Doppler shift attenuation of gammas emitted in the reversed kinematics ^{12}C + ^{35}Cl reaction. Energies and the transition probabilities for the observed negative-parity states agree with the shell-model predictions. The lifetimes of the intruder positive-parity states in ^{45}Sc and ^{45}Ti suggest a deformation ($\beta \approx 0.25$) associated with the particle-hole excitation in the nuclei.

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1. Abstract of published paper: *Acta Physica Polonica B* **27**, 145 (1996) (Proceedings of High Angular Momentum Phenomena Workshop, Piaski, Poland, August 23-26).
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A NEW SPONTANEOUS FISSION MODE FOR ^{252}Cf: HYPERDEFORMATION, CLUSTER RADIOACTIVITY, NEW LEVELS[1]

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Direct measurements of yields and neutron multiplicities were made for Sr-Nd, Zr-Ce, Mo-Ba, Ru-Xe, and Pd-Te from γ-ray coincidence studies in spontaneous fission of ^{252}Cf. Strong enhancement of the 7-10ν emission channels is seen in the Mo-Ba data. Unfolding the Mo-Ba data revealed a new fission mode associated with the enhanced ν yields with much lower total kinetic energy going by ^{108}Mo-^{144}Ba, ^{107}Mo-^{145}Ba, and/or ^{106}Mo-^{146}Ba. Analysis indicates one or more of ^{144,145,146}Ba are hyperdeformed with 3:1 axis ratio. Theoretical calculations predict a third minimum in the PES for ^{252}Cf with $\beta_2 \sim 0.9$ and $\beta_3 \sim 0.7$. Zero neutron emission channels, a new form of cluster radioactivity, are seen in 8 and 7 correlated pairs in SF of ^{252}Cf and ^{242}Pu, respectively, with the odd-odd zero neutron channels yields strongly enhanced as predicted for cluster radioactivity. New level structures and isotopes include new octupole deformations, identical bands, and other structures.

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1. Abstract of published paper: pp. 187-199 in *Low-Energy Nuclear Dynamics*, St. Petersburg, Russia, April 18-22, 1995 (Proceedings of XV European Physical Society Nuclear Physics Divisional Conference) World Scientific Publishing Co., Singapore, 1996.
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STRUCTURE OF PROTON DRIP-LINE NUCLEI AROUND DOUBLY MAGIC ^{48}Ni (Ref. 1)

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Properties of proton-rich nuclei around doubly magic $^{48}_{28}Ni_{20}$ are studied in the framework of the self-consistent mean-field theory (Hartree-Fock, Hartree-Bock-Bogoliubov, and relativistic mean field). Various effective interactions are employed to investigate two-proton separation energies, deformations, single-particle levels, proton average potentials, and diproton partial decay half-lives in this mass region.

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1. Abstract of published paper: *Phys. Rev. C* **53**, 740 (1996)
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GROUND-STATE PROPERTIES OF EXOTIC Si, S, Ar, AND Ca ISOTOPES[1]

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Masses, deformations, radii, two-neutron separation energies and single-particle properties of Si, S, Ar, and Ca isotopes are investigated in the framework of the self-consistent mean-field theory. In particular, the role of the N=28 gap in the neutron-rich isotopes and differences between proton and neutron deformations are discussed.

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1. Abstract of published paper: *Nucl. Phys. A* **597**, 327 (1996).
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COMMENT ON "SHAPE AND SUPERDEFORMED STRUCTURE IN Hg ISOTOPES IN RELATIVISTIC MEAN-FIELD MODEL" AND "STRUCTURE OF NEUTRON-DEFICIENT Pt, Hg, AND Pb ISOTOPES"[1]

K. Heyde,[2] C. De Coster,[2] P. Van Duppen,[3] M. Huyse,[3] J. L. Wood,[4] W. Nazarewicz[5]

It is pointed out that the results of relativistic mean-field calculations for neutron-deficient Pt, Hg, and Pb isotopes by S. K. Patra et al. [Phys. Rev. C 50, 1924 (1994)] and S. Yoshida et al. [Phys. Rev. C 50, 1398 (1994)] contradict the large body of experimental data on these nuclei. In particular, we question their predictions of deformed ground states in the Pb isotopes, and prolate and superdeformed ground states in the Hg isotopes.

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1. Abstract of published paper: *Phys. Rev. C* **53**, 1035 (1996).
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ROTATIONAL INERTIA OF SUPERDEFORMED NUCLEI: INTRUDER ORBITALS, PAIRING, AND IDENTICAL BANDS[1]

G. de France,[2] C. Baktash, B. Haas,[2] W. Nazarewicz[3]

The phenomenon of identical bands is studied by analyzing the distributions of fractional changes in the dynamical moments of inertia of pairs of bands in superdeformed (SD) nuclei. These distributions are found to exhibit a peak with a centroid at nearly zero. Their widths increase in going from the SD bands in the mass A ~ 150, to the SD bands in the mass ~190, and to the normally deformed bands in the rare-earth region. Consequently, there exists a significant excess of identical bands in SD nuclei compared to the

normally deformed nuclei at low spins. This differnce may be attributed to the weaker pairing correlations and the stabilizing role of intruder orbitals on the structures of SD bands.

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1. Abstract of published paper: *Phys. Rev. C* **53**, 1070 (1996).
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NEUTRON RADII AND SKINS IN THE HARTREE-FOCK-BOGOLIUBOV CALCULATIONS[1]

J. Dobaczewski,[2] W. Nazarewicz,[3] T. R. Werner[2]

The systematic predictions for proton and neutron radii in even-even nuclei made by the self-consistent Skyrme-Hartree-Fock-Bogoliubov theory are examined. Such an approach allows nuclei far from stability to be described, where the spatial extensions of a nuclear system crucially depend on the continuum effects. Interest is concentrated on the influence of spherical shell structure on global behavior of radii. The (N,Z) localization of neutron and proton skins is discussed.

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1. Abstract of published paper: *Z. Phys. A* **354**, 27 (1996).
2. JIHIR guest assignee from Warsaw University, Warsaw, Poland.
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MEAN-FIELD DESCRIPTION OF GROUND-STATE PROPERTIES OF DRIP-LINE NUCLEI: PAIRING AND CONTINUUM EFFECTS[1]

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Ground-state properties of exotic even-even nuclei with extreme neutron-to-proton ratios are described in the framework of self-consistent mean-field theory with pairing formulated in coordinate space. This theory properly accounts for the influence of the particle continuum, which is particularly important for weakly bound systems. The pairing properties of nuclei far from stability are studied with several interactions emphasizing different aspects, such as the range and density dependence of the effective interaction. Measurable consequences of spatially extended pairing fields are presented, and the sensitivity of the theoretical predictions to model details is discussed.

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1. Abstract of published paper: *Phys. Rev. C* **53**, 2809 (1996)
2. Warsaw University, Warsaw, Poland.
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LIPKIN-NOGAMI PAIRING SCHEME IN SELF-CONSISTENT NUCLEAR STRUCTURE CALCULATIONS[1]

P.-G. Reinhard,[2] W. Nazarewicz,[3] M. Bender,[4] J. A. Maruhn[4]

Investigated is the pairing treatment with approximate particle number projection, known as the Lipkin-Nogami scheme, in connection with nuclear Hartree-Fock models. A prescription for the pairing

strength is developed. It is based on the average gap method and employs a Thomas-Fermi model to estimate the average level density at the Fermi surface. The second-order variation of the Skyrme energy functional gives feedback to the self-consistent density and thus to the mean field. This effect turns out to be small but non-negligible. The Lipkin-Nogami scheme is compared with the conventional treatment of pairing based on the BCS approximation. The bulk observables, especially those which are related to surface properties, depend on the pairing scheme employed, with the differences most noticeable for light nuclei. Pronounced effects on deformation energy surfaces were found, leading to sizable differnces in the deformation energies.

1. Abstract of published paper: *Phys. Rev. C* **53**, 2776 (1996).
2. JIHIR guest assignee from University of Erlangen, Erlangen, Germany.
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NEW SPONTANEOUS FISSION MODE FOR ^{252}Cf: INDICATION OF HYPERDEFORMED ^{144,145,146}Ba AT SCISSION[1]

G. M. Ter-Akopian,[2] J. H. Hamilton,[3] Yu. Ts. Oganessian,[2] A. V. Daniel,[2] J. Kormicki,[4] A. V. Ramayya,[3] G. S. Popeko,[2] B.R.S. Babu,[3] Q.-H. Lu,[3] K. Butler-Moore,[3] W.-C. Ma,[5] S. Cwiok,[6] W. Nazarewicz,[7] J. K. Deng,[3] D. Shi,[3] J. Kliman,[8] M. Morhac,[8] J. D. Cole,[9] R. Aryaeinejad,[9] N. R. Johnson,[10] I. Y. Lee,[11] F. K. McGowan,[12] J. X. Saladin[13]

From γ-ray coincidence studies following spontaneous fission of ^{252}Cf, direct measurements of yields and neutron multiplicities were made for Sr-Nd, Zr-Ce, Mo-Ba, Ru-Xe, and Pd-Te correlated pairs. A strong enhancement of the 7-10 neutron channels for Mo-Ba pairs is observed. A new fission mode associated with the enhanced neutron yields is identified. These data can be interpreted in terms of one or more of ^{144,145,146}Ba being hyperdeformed at scission. Mean-field calculations predict a hyperdeformed third minimum in ^{252}Cf and an extremely deformed ^{146}Ba fragment at scission.

1. Abstract of published paper: *Phys. Rev. Lett.* **77**, 32 (1996).
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INTRINSIC REFLECTION ASYMMETRY IN ATOMIC NUCLEI[1]

P. A. Butler[2] and W. Nazarewicz[3]

The experimental and theoretical evidence for intrinsic reflection-asymmetric shapes in nuclei is reviewed. The theoretical methods discussed cover a wide spectrum, from mean-field theory and its extensions to algebraic and cluster approaches. The experimental data for nuclear ground states and at low

and high spin, cited as evidence for reflection asymmetry, are collected and categorized. The extensive data on electric dipole transition moments and their theoretical interpretation are surveyed, along with available data on electric octupole moments. The evidence for reflection-asymmetric molecular states in light nuclei is summarized. The application of reflection-asymmetric theories to descriptions of the fission barrier, bimodal fission, superdeformation, and hyperdeformations is reviewed, and some other perspectives in the wider context of nuclear physics are also given.

1. Abstract of published paper: *Rev. Mod. Phys.* **68**, 349 (1996).
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SHELL STRUCTURE OF THE SUPERHEAVY ELEMENTS[1]

S. Cwiok,[2] J. Dobaczewski,[3] P.-H. Heenen,[4] P. Magierski,[5] W. Nazarewicz[6]

Ground-state properties of the superheavy elements (SHE) with $108 \leq Z \leq 128$ and $150 \leq N \leq 192$ are investigated using both the Skyrme-Hartree-Fock method with a density-independent contact pairing interaction and the macroscopic-microscopic approach with an average Woods-Saxon potential and a monopole pairing interaction. Detailed analysis of binding energies, separation energies, shell effects, single proton and neutron states, equilibrium deformations, Q_α-values, and other observables is given.

1. Abstract of published paper: *Nucl. Phys. A* **611**, 211 (1996).
2. JIHIR guest assignee from Warsaw University of Technology, Warsaw, Poland.
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ADDITIVITY OF QUADRUPOLE MOMENTS IN SUPERDEFORMED BANDS: SINGLE-PARTICLE MOTION AT EXTREME CONDITIONS[1]

W. Satula,[2] J. Dobaczewski,[3] J. Dudek,[4] W. Nazarewicz[5]

Quadrupole and hexadecapole moments of superdeformed bands in the $A \sim 150$ mass region have been analyzed in the cranking Skyrme-Hartree-Fock model. It is demonstrated that, independently of the intrinsic configuration and of the proton and neutron numbers, the charge moments calculated with respect to the doubly magic superdeformed core of ^{152}Dy can be expressed very precisely in terms of independent contributons from the individual hole and particle orbitals. This result, together with earlier studies of the moments of inertia distributions, suggests that many features of the superdeformed bands in the $A \sim 150$ mass region can be very well understood in terms of an almost undisturbed single-particle motion.

1. Abstract of published paper: *Phys. Rev. Lett.* **77**, 5182 (1996).
2. JIHIR guest assignee from Warsaw University, Warsaw, Poland.
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QUADRUPOLE AND HEXADECAPOLE CORRELATIONS IN ROTATING NUCLEI STUDIED WITHIN THE SINGLE-j SHELL MODEL[1]

P. Magierski,[2] K. Burzynski,[3] E. Perlinska,[3] J. Dobaczewski,[3] W. Nazarewicz[4]

The influence of quadrupole and hexadecapole residual interactions on rotational bands is investigated in a single-j shell model. An exact shell-model diagonalization of the quadrupole-plus-hexadecapole Hamiltonian demonstrates that the hexadecapole-hexadecapole interaction can sometimes produce a staggering of energy levels in the yrast sequence; however, long and regular $\Delta I=2$ sequences are not obtained. The shell-model results are discussed in terms of the intrinsic deformations extracted by means of the self-consistent Hartree-Fock method. The angular momentum dependence of intrinsic quadrupole and hexadecapole moments $Q_{2\mu}$ and $Q_{4\mu}$ is investigated.

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COEXISTENCE OF COLLECTIVE AND NON-COLLECTIVE STRUCTURES IN THE ODD-A $f_{7/2}$ NUCLEI[1]

P. Bednarczyk,[2] J. Styczen,[2] R. Broda,[2] M. Lach,[2] W. Meczynski,[2] W. Nazarewicz,[3] W. E. Ormand,[4] W. Satula,[5] D. Bazzacco,[6] F. Brandolini,[6] G. de Angelis,[7] S. Lunardi,[6] L. Müller,[6] N. H. Medina,[6] C. M. Petrache,[7] C. Rossi Alvarez,[6] F. Scarlassara,[6] G. F. Segato,[6] C. Signorini,[6] F. Soramel[8]

High-spin states in ^{43}Ca, ^{45}Sc, and ^{45}Ti were studied with the GASP multidetector array coupled with the recoil mass spectrometer. The nuclei were excited in the 60 MeV ^{18}O + ^{30}Si reaction. Lifetimes were extracted from the analysis of the Doppler-shift attenuation of γ-rays observed in the reversed ^{35}Cl + ^{12}C reaction. The measurements suggest significant deformations of the positive-parity intruder bands in ^{45}Sc and ^{45}Ti. These bands are predicted by the mean-field calculations to be the cross-shell particle-hole excitation associated with a strong quadrupole core polarization. Spherical shell-model calculations reproduce observed excitation energies and transition rates in both spherical and deformed structures.

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DEFORMED NUCLEAR HALOS[1]

T. Misu,[2] W. Nazarewicz,[2] S. Åberg[3]

Deformation properties of weakly bound nuclei are discussed in the deformed single-particle model. It is demonstrated that in the limit of a very small binding energy the valence particles in specific orbitals, characterized by a very small projection of single-particle angular momentum onto the symmetry axis of a nucleus, can give rise to the halo structure which is completely decoupled from the rest of the system. The

quadrupole deformation of the resulting halo is completely determined by the intrinsic structure of a weakly bound orbital, irrespective of the shape of the core.

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ALPHA DECAY AND SHAPE COEXISTENCE IN THE ALPHA-ROTOR MODEL[1]

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The particle-plus-rotor was employed to study the fine structure seen in the alpha decay of even-even neutron-deficient nuclei in the Hg-Po region. The configuration mixing resulting from the shape coexistence between well-deformed prolate bands and spherical (or quasi-rotational oblate) structures in the daughter nuclei was considered. Experimental alpha-decay branching ratios are reproduced within one order of magnitude, except for the case of ^{180}Hg which daughter nucleus, ^{176}Pt, is expected to be triaxial in its ground state. The effect of configuration mixing on the relative intensities is discussed in detail, together with the sensitivity of results to the choice of the alpha-nucleus optical model parameters.

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CORRECTION FACTORS FOR REACTIONS INVOLVING $q\bar{q}$ ANNIHILATION OR PRODUCTION[1]

L. Chatterjee[2] and C. Y. Wong

In reactions with $q\bar{q}$ production or $q\bar{q}$ annihilation, initial- and final-state interactions give rise to large corrections to the lowest-order cross sections. We evaluate the correction factor first for low relative kinetic energies by studying the distortion of the relative wave function. We then follow the procedure of Schwinger to interpolate this result with the well-known perturbative QCD vertex correction factors at high energies to obtain an explicit semiempirical correction factor applicable to the whole range of energies. The correction factor predicts an enhancement for $q\bar{q}$ in color-singlet states and a suppression for color-octet states, the effect increasing as the relative velocity decreases. Consequences on dilepton production in the quark-gluon plasma, the Drell-Yan process, and heavy quark production processes are discussed.

1. Abstract of published paper: *Phys. Rev. C* **51**, 2125 (1995).
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SCHWINGER PARTICLE-PRODUCTION MECHANISM FOR A FINITE-LENGTH FLUX TUBE WITH TRANSVERSE CONFINEMENT[1]

C. Y. Wong, R. C. Wang,[2] J. S. Wu[3]

Previous results for the pair production probability in a strong electric field with a finite longitudinal separation are generalized to the case of a finite-length flux tube with transverse confinement. The threshold length of the flux tube, below which pair production cannot occur, increases as a result of transverse confinement.

1. Abstract of published paper: *Phys. Rev. D* **51**, 3940 (1995).
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BOUNDARY AND COULOMB EFFECTS ON BOSON SYSTEMS IN HIGH-ENERGY HEAVY-ION COLLISIONS[1]

M.G.-H. Mostafa[2] and C. Y. Wong

The boundary of a boson system plays an important role in determining the momentum distribution of the bosons. For a boson system with a cylindrical boundary, the momentum distribution is enhanced at high transverse momenta but suppressed at low transverse momenta, relative to a Bose-Einstein distribution. The boundary effects on systems of massless gluons and massive pions are studied. For gluons in a quark-gluon plasma, the presence of the boundary may modify the signals for the quark-gluon plasma. For pions in a pion system in heavy-ion collisions, Coulomb final-state interactions with the charged nuclear participants in the vicinity of the central rapidity region further modify the momentum distribution at low transverse momenta. By including both the boundary effect and the Coulomb final-state interactions, we are able to account for the behavior of the π^- transverse momentum spectrum observed in many heavy-ion experiments, notably at low transverse momenta.

1. Abstract of published paper: *Phys. Rev. C* **51**, 2135 (1995).
2. Ain Shams University, Cairo, Egypt.

BOUNDARY EFFECTS AS SIGNALS FOR THE QUARK-GLUON PLASMA[1]

C. Y. Wong

The boundary of a quark-gluon plasma affects the momentum distribution of quarks in a quark-gluon plasma. The boundary effects can be used to indicate the presence of the plasma.

1. Abstract of published paper: *pp. 285-297 in Proceedings of 3rd International Workshop on Relativistic Aspects of Nuclear Physics, Rio de Janeiro, Brazil, August 25-27, 1993* (World Scientific Publishing Co., Singapore, 1995).

THERMAL DIMUONS AT RHIC ENERGIES[1]

M.G.-H. Mostafa,[2] C. Y. Wong, L. Chatterjee,[3] Z. Q. Wang[4]

The dimuon production rate from a thermalized quark-gluon plasma in heavy-ion collisions at RHIC energies is calculated. Higher-order QCD corrections are included by using an analytical correction factor $K^{(i)}$, which gives very good agreement with experimental Drell-Yan data, and predicts a large enhancement of the thermal dimuon emission over the lowest-order rates. The thermal dimuon yields are compared with the expected production from open-charm decays and Drell-Yan background and assess the prospects of observing thermal dimuons from the quark-gluon plasma at invariant masses of a few GeV.

1. Abstract of published paper: *Int. J. Mod. Phys. E* **5** (1996).
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SUPPRESSION OF ψ′ AND J/ψ IN HIGH-ENERGY HEAVY-ION COLLISIONS[1]

C. Y. Wong

The experimental ratio of ψ′ to J/ψ is approximately a constant in pA collisions, but decreases as the transverse energy increases in nucleus-nucleus collisions. These peculiar features can be explained as arising from approximately the same $c\bar{c}$-baryon absorption cross section for ψ′ and J/ψ but greater disruption probabilities for ψ′ than for J/ψ due to the interaction of the $c\bar{c}$ system with soft particles produced in baryon-baryon collisions.

1. Abstract of published paper: *Phys. Rev. Lett.* **76**, 196 (1996).

EXCESS DILEPTONS IN HIGH-ENERGY NUCLEUS-NUCLEUS COLLISIONS[1]

C. Y. Wong and Z. Q. Wang[2]

It has been observed recently that while continuum dilepton production and open-charm production in high-energy pA collisions can be described in terms of the superposition of pp collisions, dilepton yields in S+U collisions are in excess of similar extrapolations. This feature can be explained as arising from the interaction of gluons produced in different soft baryon-baryon collisions, leading to additional open-charm pairs in nucleus-nucleus collisions but not in pA collisions.

1. Abstract of published paper: *Phys. Lett. B* **367**, 50 (1996).
2. China Institute of Atomic Energy, Beijing, China.

ψ' AND J/ψ SUPPRESSION IN HIGH-ENERGY NUCLEON-NUCLEUS AND NUCLEUS-NUCLEUS COLLISIONS[1]

C. Y. Wong

The observed features of ψ' to J/ψ suppression in pA and nucleus-nucleus collisions can be explained in terms of a two-component absorption model. For the hard component of the absorption due to the interaction of the produced $c\bar{c}$ systems with baryons at high relative energies, the absorption cross sections are insensitive to the radii of the $c\bar{c}$ systems, as described by the additive quark model. For the soft component due to the low-energy $c\bar{c}$ interactions with soft particles produced by other baryon-baryon collisions, the absorption cross sections are greater for ψ' than for J/ψ, because the breakup threshold for ψ' is much smaller than for ψ.

1. Abstract of published paper: *pp. 140-144 in Nuclear Physics — At the Frontiers of Knowledge (Proceedings of International Nuclear Physics Conference — INPC '95, Beijing, China, August 21-26, 1995)* World Scientific Publishing Co., Singapore, 1996.

SINGULARITY-FREE BREIT EQUATION FROM CONSTRAINT TWO-BODY DIRAC EQUATIONS[1]

H. W. Crater,[2] C. W. Wong,[3] C. Y. Wong

The relation between two approaches to the quantum relativistic two-body problem is examined: (1) the Breit equation, and (2) the two-body Dirac equations derived from constraint dynamics. In applications to quantum electrodynamics, the former equation becomes pathological if certain interaction terms are not treated as perturbations. The difficulty comes from singularities which appear at finite separations r in the reduced set of coupled equations for attractive potentials even when the potentials themselves are not singular there. They are known to give rise to unphysical bound states and resonances. In contrast, the two-body Dirac equations of constraint dynamics do not have these pathologies in many nonperturbative treatments. To understand these marked differences, we first express these constraint equations which have an "external potential" form similar to coupled one-body Dirac equations in a hyperbolic form. These coupled equations are then recast into two equivalent equations: (1) a covariant Breit-like equation with potentials that are exponential functions of certain "generator" functions, and (2) a covariant orthogonality constraint on the relative momentum. This reduction enables us to show in a transparent way that finite-r singularities do not appear as long as the exponential generators of the interaction are themselves nonsingular for finite r. These singularity-free Breit equations could be used to provide nonperturbative descriptions of strong field problems.

1. Abstract of published paper: *Int. J. Mod. Phys. E* **5** (1996).
2. University of Tennessee Space Institute, Tullahoma, TN.
3. University of California, Los Angeles.

EFFECTS OF SCREENING ON QUARK-ANTIQUARK CROSS SECTIONS IN QUARK-GLUON PLASMA[1]

C. Y. Wong and L. Chatterjee[2]

Lowest-order cross sections for $q\bar{q}$ production and annihilation can be approximately corrected for higher-order QCD effects by using a corrective K-factor. For energies where quark masses cannot be ignored, the K-factor is dominated by the wave function distortion arising from the initial- or final-state

interaction between the quark and the antiquark. This K-factor is evaluated for $q\bar{q}$ production and annihilation in a quark-gluon plasma by taking into account the effects of Debye screening through a color-Yukawa potential. The corrective K-factor is presented as a function of dimensionless parameters which may find applications in other systems involving attractive or repulsive Yukawa interactions. Prominent peaks of the K-factor occur for an attractive $q-\bar{q}$ color-Yukawa interaction with Debye screening lengths of 0.835 and 3.23 times the Bohr radius, corresponding to two lowest s-wave $q\bar{q}$ bound states moving into the continuum to become $q\bar{q}$ resonances as the Debye screening length decreases. These resonances, especially the $c\bar{c}$ and the $b\bar{b}$ resonances, may be utilized to search for the quark-gluon plasma by studying the systematics of the temperature dependence of heavy quark pair production just above the threshold.

1. Abstract of paper to be published in *Zeitschrift für Physik.*
2. Guest assignee from Jadavpur University, Calcutta, India.

EFFECTS OF FINAL-STATE INTERACTION AND SCREENING ON STRANGE AND HEAVY QUARK PRODUCTION[1]

C. Y. Wong and L. Chatterjee[2]

Final-state interaction and screening have a great influence on $q\bar{q}$ production cross sections, which are important quantities in many problems in quark-gluon plasma physics. They lead to an enhancement of the cross section for a $q\bar{q}$ color-singlet state and a suppression for a color-octet state. The effects are large near the production threshold. The presence of screening gives rise to resonances for $q\bar{q}$ production just above the threshold at specific plasma temperatures. These resonances, especially $c\bar{c}$ and $b\bar{b}$ resonances, may be utilized to search for the quark-gluon plasma by studying the temperature dependence of heavy quark pair production just above the threshold.

1. Abstract of paper to be published in Proceedings of Strangeness '96 Conference, Budapest, Hungary, May 15-17, 1996.
2. Guest assignee from Jadavpur University, Calcutta, India.

COLOR-OCTET FRACTION IN J/ψ PRODUCTION[1]

C. Y. Wong and C. W. Wong[2]

The cross section between a $c\bar{c}$ object and a nucleon is small if the object is in a color-singlet state, but very large and insensitive to its size if it is in a color-octet state. This property is used to estimate the fraction of $c\bar{c}$ color-octet states formed after the initial hard-scattering processes by studying the effective J/ψ absorption in a nucleus. The experimental NA3 and E772 data of pA $\rightarrow$ ψX reveal the presence of anomalously large effective absorption of J/ψ at large x_F, which indicates a large color-octet fraction in J/ψ production at large x_F.

1. Abstract of paper submitted for publication in *Physical Review Letters.*
2. University of California, Los Angeles.

SUPPRESSION OF J/ψ AND ψ′ PRODUCTION IN HIGH-ENERGY Pb ON Pb COLLISIONS[1]

C. Y. Wong

The anomalous suppression of J/ψ production in Pb-Pb collisions at 158A GeV observed recently by NA50 is explained as due to the transition to a new phase of strong J/ψ absorption, which sets in when the local energy density exceeds about 3.4 GeV/fm^3. The observed decrease in ψ′/ψ in Pb-Pb collisions relative to nucleon-nucleon collisions can be understood as arising from a larger effective cross section for ψ′ than J/ψ for absorption by soft particles and by matter in the new phase.

1. Abstract of paper submitted for publication in *Physical Review Letters*.

J/ψ AND ψ′ SUPPRESSION IN HIGH-ENERGY HEAVY-ION COLLISIONS[1]

C. Y. Wong

The anomalous suppression of J/ψ production in Pb-Pb collisions at 158A GeV observed by the NA50 Collaboration can be explained as due to the occurrence of a new phase of strong J/ψ absorption, which sets in when the local energy density exceeds about 3.4 GeV/fm^3. The peculiar behavior of the ψ′/ψ ratio in p-A and nucleus-nucleus collisions can be understood as due to approximately equal ψ-N and ψ′-N absorption cross sections, but greater absorption cross sections for ψ′ than J/ψ with regard to absorption by soft particles and matter in the new phase.

1. Abstract of paper to be published in Proceedings of Quark Matter '96, Twelfth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Heidelberg, Germany, May 20-24, 1996.

SHELL MODEL THE MONTE CARLO WAY[1]

W. E. Ormand[2]

The formalism for the auxiliary-field Monte Carlo approach to the nuclear shell model is presented. The method is based on a linearization of the two-body part of the Hamiltonian in an imaginary-time propagator using the Hubbard-Stratonovich transformation. The foundation of the method, as applied to the nuclear many-body problem, is discussed. Topics presented in detail include: (1) the density-density formulation of the method, (2) computation of the overlaps, (3) the sign of the Monte Carlo weight function, (4) techniques for performing Monte Carlo sampling, and (5) the reconstruction of response functions from an imaginary-time auto-correlation function using MaxEnt techniques. Results obtained using schematic interactions, which have no sign problem, are presented to demonstrate the feasibility of the method, while an extrapolation method for realistic Hamiltonians is presented. In addition, applications at finite temperature are outlined.

1. Abstract of paper to be published in Proceedings of International Workshop on Structure and Dynamics of Quantum Many-Body Systems, Aizn, Japan, October 19-21, 1994.

2. Guest assignee from Louisiana State University, Baton Rouge.

NEUTRINO CAPTURE CROSS SECTIONS FOR ^{40}Ar AND β-DECAY OF ^{40}Ti (Ref. 1)

W. E. Ormand,[2] P. M. Pizzochero,[3] P. F. Bortignon,[3] R. A. Broglia[3]

Shell-model calculations of solar neutrino absorption cross sections for ^{40}Ar, the proposed component of the ICARUS detector, are presented. It is found that low-lying Gamow-Teller transitions lead to a significant enhancement of the absorption rate over that expected from the Fermi transition between the isobaric analog states, leading to an overall absorption cross section for ^{8}B neutrinos of $(11.5 \pm 0.7) \times 10^{-43}$ cm^2 or a total expected rate of 6.7 ± 2.5 SNU. We also note that the pertinent Gamow-Teller transitions in ^{40}Ar are experimentally accessible from the β-decay of the mirror nucleus ^{40}Ti. Predictions for the branching ratios to states in ^{40}Sc are presented, and the theoretical half-life of 55 ± 5 ms is found to be in good agreement with the experimental value of 56^{+18}_{-12} ms.

1. Abstract of published paper: *Phys. Lett. B* **345**, 343 (1995).
2. Guest assignee from Louisiana State University, Baton Rouge.
3. University of Milan, Milan, Italy

ISOSPIN-MIXING CORRECTIONS FOR fp-SHELL FERMI TRANSITIONS[1]

W. E. Ormand[2] and B. A. Brown[3]

Isospin-mixing corrections for super-allowed Fermi transitions in fp-shell nuclei are computed within the framework of the shell model. The study includes three nuclei that are part of the set of nine accurately measured transitions, as well as five cases that are expected to be measured in the future at radioactive beam facilities. Included also are some new calculations for ^{10}C. With the isospin-mixing corrections applied to the nine accurately measured ft values, the conserved-vector current hypothesis and the unitarity condition of the Cabbibo-Kobayashi-Maskawa matrix are tested.

1. Abstract of published paper: *Phys. Rev. C* **52**, 2455 (1995).
2. Guest assignee from Louisiana State University, Baton Rouge.
3. Michigan State University, East Lansing.

RESPONSE OF MICA TO WEAKLY INTERACTING MASSIVE PARTICLES[1]

J. Engel,[2] M. T. Ressell,[3] I. S. Towner,[4] W. E. Ormand[5]

Spin-dependent cross sections are calculated for the scattering from mica of hypothetical weakly interacting dark-matter particles such as neutralinos. The most abundant odd-A isotopes in mica, ^{27}Al and ^{39}K, require different shell-model treatments. The calculated cross sections will allow the interpretation of ongoing experiments that look for tracks due to the interaction of dark-matter particles with nuclei in ancient mica.

1. Abstract of published paper: *Phys. Rev. C* **52**, 2216 (1995).
2. University of North Carolina, Chapel Hill.
3. California Institute of Technology, Pasadena.
4. Chalk River Laboratories, Chalk River, Ontario, Canada.
5. Guest assignee from Louisiana State University, Baton Rouge.

PROPERTIES OF PROTON DRIP-LINE NUCLEI AT THE sd-fp-SHELL INTERFACE[1]

W. E. Ormand[2]

Properties of proton-rich nuclei at the sd-fp-shell boundary with $37 \leq A \leq 48$ are investigated within the framework of the nuclear shell model. Predicted binding energies, one- and two-proton separation energies, and β-endpoint energies are presented. Half-lives associated with one- and two-proton emissions are compared with β decay, and it is determined that the best candidates for the observation of correlated two-proton emission are ^{38}Ti and ^{45}Fe. The predicted branching ratios for β decay as a function of excitation energy in the daughter nucleus are shown. Where available, β-decay half-lives are compared with experiment and are found to be in overall good agreement.

1. Abstract of published paper: *Phys. Rev. C* **53**, 214 (1996).
2. Guest assignee from Louisiana State University, Baton Rouge.

TEMPERATURE DEPENDENCE OF THE WIDTH OF THE GIANT DIPOLE RESONANCE[1]

W. E. Ormand,[2] *P. F. Bortignon,*[3] *R. A. Broglia*[3]

The giant dipole resonance (GDR) in ^{120}Sn and ^{208}Pb is studied as a function of excitation energy, angular momentum, and intrinsic width within the context of the adiabatic model. Theoretical evaluations of the full width at half maximum (FWHM) for the GDR strength function are compared with recent experimental data and are found to be in good agreement.

1. Abstract of published paper: *pp. 57c-62c in Giant Resonances (Proceedings of the Groningen Conference on Giant Resonances, Groningen, The Netherlands, June 28 - July 1, 1995)* Elsevier Science, Amsterdam, 1996 (*Nucl. Phys. A* **599**, 1c (1996).
2. Guest assignee from Louisiana State University, Baton Rouge.
3. University of Milan, Milan, Italy.

TEMPERATURE DEPENDENCE OF THE WIDTH OF THE GIANT DIPOLE RESONANCE IN ^{120}Sn AND ^{208}Pb (Ref. 1)

W. E. Ormand,[2] *P. F. Bortignon,*[3] *R. A. Broglia*[3]

The giant dipole resonance (GDR) in ^{120}Sn and ^{208}Pb is studied as a function of excitation energy, angular momentum, and intrinsic width. Theoretical evaluations of the full width at half maximum (FWHM) for the GDR strength function are compared with recent experimental data and are found to be in good agreement. Differences observed between ^{120}Sn and ^{208}Pb are attributed to strong shell corrections in ^{208}Pb favoring spherical shapes at low temperatures. At high temperature, the FWHM in ^{120}Sn exhibits effects due to the evaporation width of the compound nucleus.

1. Abstract of paper to be published in *Physical Review Letters*.
2. Guest assignee from Louisiana State University, Baton Rouge.
3. University of Milan, Milan, Italy.

ANGULAR MOMENTUM DEPENDENCE OF THE GDR WIDTH IN Sn NUCLEI AT FIXED EXCITATION ENERGY[1]

M. Mattiuzzi,[2] A. Bracco,[2] F. Camera,[2] W. E. Ormand,[3] J. J. Gaardhoje,[4] A. Maj,[4] B. Million,[2] M. Pignanelli,[2] T. Tveter[4]

High-energy γ-rays from the decay of the giant dipole resonance (GDR) in the hot ^{106}Sn compound nucleus and its daughters were measured in coincidence with heavy recoiling evaporation residues. The compound nucleus was formed at excitation energy $E^* = 80$ MeV using the reaction ^{56}Ni + ^{48}Ti at a bombarding energy of 260 MeV. The analysis yields the GDR width for two different intervals of angular momentum $\langle J \rangle = 24$ and 34 $\hbar$. The present data, combined with previous data at higher angular momenta, permit a study of the angular momentum dependence of the GDR width for $10 \le J \le 60$ $\hbar$ at approximately fixed temperature. The width of the GDR is found to be roughly constant for $J < 35$ $\hbar$, increasing rapidly for higher angular momenta. The data are found to be in good agreement with theoretical calculations within an adiabatic model describing thermal fluctuations of the nuclear shape. The model also reproduces the much weaker angular momentum dependence of the GDR width in the heavier nucleus ^{176}W.

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1. Abstract of paper to be published in *Nuclear Physics A*.
2. University of Milan, Milan, Italy.
3. Guest assignee from Louisiana State University, Baton Rouge.
4. Niels Bohr Institute, Copenhagen, Denmark.

BEHAVIOR OF THE GIANT DIPOLE RESONANCE IN ^{120}Sn AND ^{208}Pb AT HIGH EXCITATION ENERGY[1]

W. E. Ormand,[2] P. F. Bortignon,[3] R. A. Broglia,[3] A. Bracco[3]

The properties of the giant dipole resonance (GDR) are calculated as a function of excitation energy, angular momentum, and the compound nucleus particle decay width in the nuclei ^{120}Sn and ^{208}Pb, and are compared with recent experimental data. Differences observed in the behavior of the full width at half maximum of the GDR for ^{120}Sn and ^{208}Pb are attributed to the fact that shell corrections in ^{208}Pb are stronger than in ^{120}Sn, and favor the spherical shape at low temperatures. The effects shell corrections have on both the free energy and the moments of inertia are discussed in detail. At high temperature, the FWHM in ^{120}Sn exhibits effects due to the evaporation width of the compound nucleus, while these effects are predicted for ^{208}Pb.

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1. Abstract of paper to be published in *Nuclear Physics A*.
2. Guest assignee from Louisiana State University, Baton Rouge.
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KN SCATTERING IN THE NONRELATIVISTIC QUARK MODEL[1]

T. Barnes[2]

KN scattering is of interest as a probe of nuclear structure and, more fundamentally, as a laboratory for the study of nonresonant hadron-hadron interactions. KN is a theoretically attractive channel because of its simplicity, having only $S = 1/2$, no one-pion exchange contributions, and no valence $q\bar{q}$ annihilation. It may therefore be useful for the study of short-ranged quark forces analogous to the NN repulsive core. Since there are two isospin states, comparison of two closely related amplitudes is possible. This contribution reviews the experimental status of S-wave KN scattering and related theoretical studies based on quark-gluon dynamics. The experimental low-energy S-wave phase shift is well established for I = 1, but is not yet well determined for I = 0. The ratio of I = 0 to I = 1 scattering lengths is an interesting number theoretically, and may discriminate between different scattering mechanisms. A measurement of these scattering lengths at DAPHNE would be a useful contribution to low-energy hadron physics.

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1. Abstract of published paper: pp. 445-458 in *Proceedings of Second Workshop on Physics and Detectors for Daphne '95, Frascati, Italy, Apr. 4-7, 1995* (Frascati Physics Series, Vol. IV, INFN, Frascati, Italy, 1996).
2. UT-ORNL Collaborative Scientist.

THEORETICAL PREDICTIONS FOR EXOTIC HADRONS[1]

T. Barnes[2]

In this contribution, current theoretical expectations for the properties of light meson "exotica," which are meson resonances outside the $q\bar{q}$ quark model, are discussed. Specifically, expectations for gluonic hadrons (glueballs and hybrids) and multiquark systems (molecules) are discussed. Experimental candidates for these states are summarized, and the relevance of a TCF to these studies is stressed.

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1. Abstract of published paper: pp. 285-306 in *Proceedings of Workshop on the Tau/Charm Factory, Argonne, IL, June 21-23, 1995* (AIP Conference Proceedings No. 349, AIP, New York, 1996).
2. UT-ORNL Collaborative Scientist.

HYBRID AND CONVENTIONAL MESONS IN THE FLUX-TUBE MODEL: NUMERICAL STUDIES AND THEIR PHENOMENOLOGICAL IMPLICATIONS[1]

T. Barnes,[2] *F. E. Close,*[3] *E. S. Swanson*[4]

Results from analytical and numerical studies of a flux-tube model of hybrid mesons are presented. Numerical results use a Hamiltonian Monte Carlo algorithm and so improve on previous analytical treatments, which assumed small flux-tube oscillations and an adiabatic separation of quark and flux-tube motion. It is found that the small oscillation approximation is inappropriate for typical hadrons and that the hybrid mass is underestimated by the adiabatic approximation. For physical parameters in the "one-bead" flux-tube model, it is estimated the lightest hybrid masses (${}_\Lambda L = {}_1P$ states) to be 1.8-1.9 GeV for $u\bar{u}$ hybrids, 2.1-2.2 GeV for $s\bar{s}$, and 4.1-4.2 GeV for $c\bar{c}$. Masses of conventional $q\bar{q}$ mesons with L = 0 to L = 3 in this model are also determined, and confirm good agreement with experimental J-averaged multiplet masses. Mass estimates are also given for hybrids with higher orbital and flux-tube excitations. The gap from the lightest hybrid level (${}_1P$) to the first hybrid orbital excitation (${}_1D$) is predicted to be $\approx$ 0.4 GeV for light quarks (q = u,d) and $\approx$ 0.3 GeV for q = c. Both ${}_1P$ and ${}_1D$ hybrid multiplets contain the exotics 1^{-+} and 2^{+-}; in addition, the ${}_1P$ has a 0^{+-} and the ${}_1D$ contains a 3^{-+}. Hybrid mesons with doubly excited flux tubes are also considered. The implications of results for spectroscopy are discussed, with emphasis on charmonium hybrids, which may be accessible at facilities such as BEPC, KEK, a Tau-Charm Factory, and in ψ production at hadron colliders.

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1. Abstract of published paper: *Phys. Rev. D* **52**, 5242 (1995).
2. UT-ORNL Collaborative Scientist.
3. Rutherford-Appleton Laboratory, Chilton, Didcot, Oxon., England.
4. North Carolina State University, Raleigh.

THEORETICAL ASPECTS OF LIGHT MESON SPECTROSCOPY[1]

T. Barnes[2]

In this pedagogical review, the theoretical understanding of light hadron spectroscopy in terms of QCD and the quark model is discussed by beginning with a summary of the known and surmised properties of QCD and confinement. Following this, the nonrelativistic quark potential model for $q\bar{q}$ mesons is reviewed, and the quarkonium spectrum and methods for identifying $q\bar{q}$ states is discussed. Finally, theoretical expectations for non-$q\bar{q}$ states (glueballs, hybrids, and multiquark systems) and the status of experimental candidates for these states are reviewed.

1. Abstract of published paper: pp. 37-72 in *Hadron Spectroscopy and the Confinement Problem (Proceedings of a NATO Advanced Study Institute on Hadron Spectroscopy and the Confinement Problem, Swansea, Wales, June 27 - July 8, 1995)* NATO ASI Series B: Physics Vol. 353, Plenum Press, NY, 1996.
2. UT-ORNL Collaborative Scientist.

THE MECHANISM OF OPEN-FLAVOR STRONG DECAYS[1]

T. Barnes[2]

In this contribution, models of two-body strong hadron decays are discussed. These models are expected to play a vital role in future attempts to identify unconventional hadrons such as glueballs and hybrids, through accurate predictions of the decay modes of conventional $q\bar{q}$ states. First, the most commonly used decay model is reviewed, which is the $^3P_0$ model developed by Micu and LeYaouanc et al., and some of its successful predictions are shown. Predictions of the $^3P_0$ model for some newly discovered states are also given. Finally, some attempts to identify the fundamental QCD process which underlies $q\bar{q}$ pair production in the $^3P_0$ model are discussed. Results indicate that the dominant $q\bar{q}$ pair production process is usually pair production through the linear scalar-confining interaction. Pair production from OGE in most cases is found to be a smaller amplitude, with the notable exception of $^3P_0 \to {}^1S_0 + {}^1S_0$ decays such as $f_0(q\bar{q}) \to \pi\pi$.

1. Abstract of published paper: pp. 33-40 in *Hadron '95 (Proceedings of 6th International Conference on Hadron Spectroscopy, Manchester, U.K., July 10-14, 1995)* World Scientific Publishing Co., Singapore, 1996.
2. UT-ORNL Collaborative Scientist.

PANEL DISCUSSION ON THE FUTURE OF HADRON SPECTROSCOPY[1]

T. Barnes[2]

This contribution addresses two of the questions which were submitted to the panel on future developments in light hadron spectroscopy. Specifically, these were the extent to which glueball spectroscopy should be explored and how far it is appropriate to continue experimental studies of the light hadron spectrum. It was suggested that at a minimum three particular glueball states should be identified, that hybrids should also be identified, and that experiments on hadrons should continue for as long as the theoretical community remains unable to predict their outcome.

1. Abstract of published paper: pp. 307-310 in *Hadron '95 (Proceedings of 6th International Conference on Hadron Spectroscopy, Manchester, U.K., July 10-14, 1995)* World Scientific Publishing Co., Singapore, 1996.
2. UT-ORNL Collaborative Scientist.

PRODUCTION AND DECAY OF "STRANGE" STATES[1]

T. Barnes[2]

In this talk, recent experimental and theoretical developments relating to hadron resonances which are external to the conventional quark model of $q\bar{q}$ mesons and qqq baryons are summarized. In view of recent developments, effort was concentrated on candidate "gluonics," the glueballs, and hybrids. Although the states which are discussed in greatest detail are mesons, hybrid baryons are also expected, and the search for these analogues of hybrid mesons will be an interesting component of future work on baryon spectroscopy.

1. Abstract of published paper: pp. 85-92 in *Proceedings of the 7th International Conference on the Structure of Baryons, Santa Fe, NM, Oct. 3-7, 1995* (World Scientific Publishing Co., Singapore, 1996)
2. UT-ORNL Collaborative Scientist.

PROSPECTS FOR DETECTING AN η'_c IN TWO-PHOTON PROCESSES[1]

T. Barnes,[2] *T. E. Browder,*[3] *S. F. Tuan*[3]

It is argued than an experimental search for an η'_c, the first radial excitation of the $\eta_c(2980)$, may be carried out using the two-photon process $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\eta'_c$. The partial width $\Gamma_{\gamma\gamma}(\eta'_c)$ is estimated, and the branching fraction $B(\eta'_c \to h)$, where h is an exclusive hadronic channel, and it is found that for $h = K^0_s K^\pm \pi^\mp$, it may be possible to observe this state in two-photon collisions at CLEO-II.

1. Abstract of published paper: *Phys. Lett. B* **385**, 391 (1996).
2. UT-ORNL Collaborative Scientist.
3. University of Hawaii at Manoa, Honolulu, HI.

ON THE MECHANISM OF OPEN-FLAVOR STRONG DECAYS[1]

E. S. Ackleh,[2] *T. Barnes,*[3] *E. S. Swanson*[4]

Open-flavor strong decays are mediated by $q\bar{q}$ pair production, which is known to occur dominantly with $^3P_0$ quantum numbers. The relation of the phenomenological $^3P_0$ model of these decays to "microscopic" QCD decay mechanisms has never been clearly established. In this paper, $q\bar{q}$ meson decay amplitudes assuming pair production from the scalar-confining interaction (sKs) and from one-gluon exchange (OGE) are investigated. The sKs pair production mechanism predicts decay amplitudes of approximately the correct magnitude and D-wave to S-wave amplitude ratios in $b_1 \to \omega\pi$ and $a_1 \to \rho\pi$ which are close to experiment. The OGE decay amplitude is found to be subdominant in most cases, a notable exception being $^3P_0 \to {}^1S_0 + {}^1S_0$. The full sKs + OGE amplitudes differ significantly from $^3P_0$ model predictions in some channels and can be distinguished experimentally, for example, through an accurate comparison of the D/S amplitude ratios in $b_1 \to \omega\pi$ and $a_1 \to \rho\pi$.

1. Abstract of published paper: *Phys. Rev. D* **54**, 6811 (1996).
2. Hewlett-Packard Corp., Atlanta, GA.
3. UT-ORNL Collaborative Scientist.
4. North Carolina State University, Raleigh.

HIGHER QUARKONIA[1]

T. Barnes,[2] F. E. Close,[3] P. R. Page,[4] E. S. Swanson[5]

Gluonic hadrons are discriminated from conventional $q\bar{q}$ states by surveying radial and orbital excitations of all I = 0 and I = 1 $n\bar{n}$ systems (n = u,d) anticipated up to 2.1 GeV. Detailed predictions are given of their quasi-two-body branching fractions, and characteristic decay modes that can isolate quarkonia are identified. Several of the "missing mesons" with $L_{q\bar{q}} = 2$ and $L_{q\bar{q}} = 3$ are predicted to decay dominantly into certain S+P and S+D modes, and should appear in experimental searches for hybrids in the same mass region. The topical issues of whether some of the recently discovered or controversial meson resonances, including glueball and hybrid candidates, can be accommodated as quarkonia are also considered.

1. Abstract of paper submitted for publication in *Physical Review D.*
2. UT-ORNL Collaborative Scientist.
3. Rutherford-Appleton Laboratory, Chilton, Didcot, Oxon., England.
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5. North Carolina State University, Raleigh.

A NEUTRON SCATTERING STUDY OF MAGNETIC EXCITATIONS IN THE SPIN LADDER $(VO)_2P_2O_7$ (Ref. 1)

A. W. Garrett,[2] S. E. Nagler,[3] T. Barnes,[4], B. C. Sales[3]

In this Letter, results are reported from inelastic neutron scattering experiments on powder samples of vanadyl pyrophosphate, $(VO)_2P_2O_7$. Evidence is seen for three magnetic excitations at 3.5 MeV, 6.0 MeV, and 14 MeV. The intensity of the 3.5 MeV mode is strong near Q = 0.8 Å^{-1}, consistent with the one-magnon gap mode reported previously and predicted by the spin-ladder model. The magnetic scattering at 14 MeV may be due to the top of the one-magnon band or the two-magnon continuum predicted in the ladder model. The 6.0 MeV mode also peaks in intensity at Q = 0.8 Å^{-1}. This mode has not been reported previously and was not anticipated by existing theoretical treatments of the spin ladder.

1. Abstract of paper submitted for publication in *Physical Review B.*
2. University of Florida, Gainesville.
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4. UT-ORNL Collaborative Scientist.

RADIAL AND ORBITAL $q\bar{q}$ EXCITATIONS: "HIGHER QUARKONIA"[1]

T. Barnes[2]

Identification of the spectrum of non-$q\bar{q}$ exotica such as glueballs, hybrids, and molecules will require a detailed understanding of radially and orbitally excited quarkonia, since these states are a background to non-$q\bar{q}$ states. The data likely to become available experimentally on these higher-mass resonances are their total widths and strong branching fractions to dominant modes. The use of these branching fractions is advocated to distinguish quarkonia from exotica; in this contribution are summarized recent detailed $^3P_0$ decay model calculations of the 374 two-body open-flavor decay modes of the 32 lightest $n\bar{n}$ states above 1S and 1P, which should be useful for this program.

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1. Abstract of paper to be published in Proceedings of Fourth Biennial Conference on Low Energy Antiproton Physics, Dinkelsbühl, Germany, August 27-31, 1996.
2. UT-ORNL Collaborative Scientist.

FOLDED POTENTIAL ANALYSIS OF THE EXCITATION OF GIANT RESONANCES BY HEAVY IONS[1]

D. J. Horen,[2] J. R. Beene, G. R. Satchler[3]

Measurements of the excitation of nuclear giant resonances by heavy-ion inelastic scattering have previously been analyzed using the deformed optical potential model. Here, these data are re-examined using a folded potential model which employs a simple, but effective, nucleon-nucleon interaction that was deduced recently from heavy-ion elastic scattering measurements. The resulting estimates of the sum-rule exhaustion by the giant quadrupole resonance increase by amounts ranging from about 20% for the lighter targets to no change for ^{208}Pb. Applying the same model to data for excitation of the giant monopole resonance, it is found that these transitions overexhaust the corresponding sum rule even more than previously indicated.

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1. Abstract of published paper: *Phys. Rev. C* **52**, 1554 (1995).
2. University of Connecticut, Storrs.
3. Guest assignee from University of Tennessee, Knoxville.

FOLDING ANALYSIS OF THE ELASTIC ^{6}Li + ^{12}C SCATTERING: KNOCK-ON EXCHANGE EFFECTS, ENERGY DEPENDENCE, AND DYNAMICAL POLARIZATION POTENTIAL[1]

D. T. Khoa,[2] G. R. Satchler,[3] W. von Oertzen[2]

Versions of the M3Y effective nucleon-nucleon interaction, with different prescriptions for the knock-on exchange contributions and density dependence, have been used in a study of the energy dependence of the nucleon optical potential in nuclear matter, as well as in a systematic folding model analysis of the elastic ^{6}Li + ^{12}C scattering data at E_{lab} = 60-318 MeV to study the energy dependence of the ^{6}Li + ^{12}C optical potential. Contributions from the (breakup) dynamical polarization potential to the real part of the ^{6}Li + ^{12}C optical potential are simulated by a surface correction using splines added to the real folded potential. This is shown to be strongest at E_{lab} = 99 MeV. The correction needed to fit the data is found to be qualitatively similar to that predicted theoretically for breakup of the ^{6}Li. The optical model analysis of the refractive ^{6}Li + ^{12}C scattering data, using different types of real folded potential, shows that the most successful is the folded potential built upon density-dependent interactions, which have parameters chosen to reproduce the saturation properties of nuclear matter and which predict a nuclear incompressibility K around 200 MeV.

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1. Abstract of published paper: *Phys. Rev. C* **51**, 2069 (1995).
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3. Guest assignee from University of Tennessee, Knoxville.

CHARACTERISTICS OF LOCAL PION-NUCLEUS POTENTIALS THAT ARE EQUIVALENT TO KISSLINGER-TYPE POTENTIALS[1]

M. B. Johnson[2] *and G. R. Satchler*[3]

The Krell-Ericson transformation provides a local potential that is exactly equivalent to the nonlocal Kisslinger-type potential. The associated scattering wave functions are related by a Perey factor. The properties of examples of these local potentials, based upon low-order multiple scattering theory at energies ranging from 20 to 291 MeV, are examined. The radial shapes of the potentials may display considerable structure in the nuclear surface. The general characteristics of the local real potentials reproduce the five features identified by Friedman from his model-independent analysis of pion scattering data. The Perey factors show a simple, mostly monotonic, behavior.

1. Abstract of published paper: *Ann. Phys.* **248**, 134 (1996).
2. Los Alamos National Laboratory, Los Alamos, NM.
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REALISTIC SCENARIO FOR THE QUASIELASTIC SCATTERING OF ^{11}Li,^{11}C + ^{12}C AT E/A ≅ 60 MeV[1]

D. T. Khoa,[2] *G. R. Satchler,*[3] *W. von Oertzen*[2]

The elastic ^{11}Li,^{11}C + ^{12}C scattering at E/A ≅ 60 MeV has been studied using a semi-microscopic version of the optical model. The real optical potential was calculated within the double-folding model using a realistic nucleon-nucleon effective interaction and a more accurate treatment of the knock-on exchange. A Hartree-Fock density was taken for ^{11}Li, while the shell model was used for ^{11,12}C. The imaginary potential was taken in standard Woods-Saxon form. The dynamic polarization potential due to the breakup effect, based on the results of realistic four-body calculations of the ^{11}Li + ^{12}C scattering, has been added to both the real and imaginary potentials for ^{11}Li. From different assumptions about the absorptive strength at the surface region, a set of parameters was found which gives a reasonable description of the quasielastic ^{11}Li,^{11}C + ^{12}C scattering data at E/A ≅ 60 MeV, as well as reproducing the observed trend for the total reaction cross section at higher energies.

1. Abstract of published paper: *Phys. Lett. B* **358**, 14 (1995).
2. Hahn-Meitner-Institut, Berlin, Germany.
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CRITICAL COMPARISON OF FOLDED POTENTIAL AND DEFORMED POTENTIAL MODELS OF HEAVY-ION INELASTIC SCATTERING[1]

J. R. Beene, D. J. Horen,[2] *G. R. Satchler*[3]

A comparative review is given of the use of the deformed potential and folded potential models for the analysis of data from the inelastic scattering of heavy ions and alpha particles. Representative cases are studied. It is shown that use of the deformed potential can very significantly underestimate the corresponding nuclear transition rate by amounts that increase strongly as the multipolarity increases. Some criticism of the implicit folding procedure is also offered.

1. Abstract of published paper: *Nucl. Phys. A* **596**, 137 (1996).
2. University of Connecticut, Storrs.
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AIRY'S POT OF GOLD: WHAT RAINBOWS ARE TEACHING US ABOUT NUCLEAR SCATTERING[1]

M. E. Brandan,[2] M. S. Hussein,[3] K. W. McVoy,[4] G. R. Satchler[5]

The origin of atmospheric rainbows has been understood for over three centuries. Nuclei often behave like spherical drops of nuclear fluid, and two decades ago it was realized that the scattering of beams of alpha particles by nuclei could exhibit some aspects of rainbow scattering. This proved invaluable in understanding the interior part of the interaction potential between an alpha particle and a nucleus. More recently it was realized that analogous phenomena could be manifest in the scattering of two nuclei (specifically, light "heavy ions") such as ^{12}C and ^{16}O. Currently this is leading to considerable insight into the interaction between such nuclei, and recently has been used to place constraints on the value of the incompressibility of nuclear matter.

1. Abstract of published paper: *Comments Nucl. Part. Phys.* **22**, 77 (1996).
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MICROSCOPIC DESCRIPTION OF THE EXCITATION OF SOME STATES IN THE $^{90,92,94,96}Zr$ ISOTOPES[1]

D. J. Horen,[2] G. R. Satchler,[3] S. A. Fayans,[4] E. L. Trykov[5]

The application of a realistic self-consistent theory of finite Fermi systems to the ground and low excited states of the $^{90,92,94,96}Zr$ isotopes is described. Results were obtained for the ground, 2_1^+ and 3_1^- states in each nucleus, and for the lowest 4^+, 5^-, 6^+, and 8^+ states in ^{90}Zr. Transition densities were generated for the excitation of each of these states and their properties examined. Transition potentials for their excitation by hadronic inelastic scattering were constructed by folding with appropriate interactions between the projectile and each target nucleon. The calculated inelastic scattering cross sections are compared in detail with experimental results, particularly those for alpha particles at 35.4 MeV and ^6Li at 70 MeV. The implications of any discrepancies found are discussed. In addition, the theoretical results were used as "experimental" data in order to test the validity of using various simple models for the analysis of data.

1. Abstract of published paper: *Nucl. Phys. A* **600**, 193 (1996).
2. University of Connecticut, Storrs.
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MISSING MONOPOLE STRENGTH IN ^{58}Ni AND UNCERTAINTIES IN THE ANALYSIS OF ALPHA-PARTICLE SCATTERING[1]

G. R. Satchler[2] and D. T. Khoa[3]

Analyses of recent measurements of the scattering of alpha particles by ^{58}Ni at energies of 129 and 240 MeV have indicated that only about a third of the sum rule limit for isoscalar monopole transitions was found in the giant resonance region of excitation energies (E_x from 10 to 30 MeV). Here, the theoretical aspects of these analyses of inelastic scattering are examined, both in the optical potentials obtained from elastic data and in the models used to represent the inelastic transitions. In particular, the folding model is introduced, and the use of folded optical and transition potentials are compared with those obtained by deforming phenomenological optical potentials. The effects of dynamic corrections to the folding interaction when this is density dependent are also studied. Both aspects are shown to have significant effects. More extensive elastic data at 139 and 340 MeV are used to illustrate the need for a density dependence in the folding interaction, as well as a need for different shapes for the real and imaginary parts of the potentials. Although these various features are shown to have non-negligible effects on the theoretical cross sections for the excitations at small angles, none of them is sufficient to account for all the apparently missing strength. Based upon the most realistic folding models, it is estimated that about 50% of the sum rule limit for monopole excitation was observed within the two components of the spectra centered at 17.42 and 20.76 MeV. The sharing between these two components depends upon the assumptions made about the distribution of the giant dipole strength which also results in angular distributions that peak at 0°. Thus, about one-half of the sum-rule limit appears to have been observed, rather than the one-third originally inferred from these data using the deformed potential model. These conclusions are based, on the one hand, upon the spectral decomposition proposed for the results of the 240 MeV experiment, and, on the other hand, upon assuming that the simple breathing mode form is adequate for the monopole transition densities. The results may be sensitive to deviations from either assumption. In a similar way, it is also inferred that at least 55%, and perhaps as much as 70%, of the isoscalar quadrupole sum-rule limit may be present in this giant resonance range of excitation energies in ^{58}Ni.

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1. Abstract of published paper: *Phys. Rev. C* **55**, 285 (1997).
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3. Chung Yuan Christian University, Taiwan, ROC.

THE INTERACTION BETWEEN LIGHT HEAVY IONS AND WHAT IT TELLS US[1]

M. E. Brandan[2] and G. R. Satchler[3]

Significant progress has been achieved during the last decade in our knowledge and understanding of the optical potential between two light heavy ions. This has mostly been a consequence of the measurement of accurate and extensive elastic differential cross sections. Some of these data, covering over eight orders of magnitude in cross section, extend to sufficiently large scattering angles that they show remarkable refractive effects which remind one of features of the scattering of alpha particles by nuclei that have been known since the work of Goldberg some twenty years ago. Refractive effects, particularly nuclear rainbows, are evident in ^{12}C + ^{12}C and ^{16}O + ^{16}O angular distributions at bombarding energies between 6 and 100 MeV per nucleon. Their angular location and cross section have led to the determination of the gross features of the local optical potentials and in many cases have removed ambiguities in the depths of the real parts of the potentials. The resulting phenomenological potentials are strongly attractive ("deep"), with relatively weak absorption, and depend upon the bombarding energy. The optical model potential for such heavy ions is no longer simply a way to parameterize scattering data (or perhaps just one of many ways). Ambiguities have been resolved, and a good understanding of the theoretical basis of its features has been

attained. The folding model is central to this understanding, coupled with increased insight into the nature of realistic effective nucleon-nucleon interactions. This report reviews the experimental evidence, its interpretation, and what we have learned from it. Much of the interpretation becomes especially transparent when couched in the language of semiclassical scattering theory. We summarize this language, as well as the basic features of the theory of the optical model.

1. Abstract of paper to be published in *Physics Reports*.
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COMPLETE $0\hbar\omega$ SHELL-MODEL MONTE CARLO CALCULATIONS OF ^{94}Ru, ^{96}Pd, ^{96,98}Cd, AND ^{100}Sn (Ref. 1)

D. J. Dean, S. E. Koonin,[2] T.T.S. Kuo,[3] K. Langanke,[2] P. B. Radha[2]

Shell-model Monte Carlo calculations are performed for nuclei in the ^{100}Sn region within the complete 0g-1d-2s oscillator shell using an effective interaction derived from the Paris nucleon-nucleon potential. Good agreement was found with empirically calculated masses, and the observed quenching of the total Gamow-Teller strengths in this mass region was reproduced.

1. Abstract of published paper: *Phys. Lett. B* **367**, 17 (1996).
2. California Institute of Technology, Pasadena.
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SHELL-MODEL MONTE CARLO STUDIES OF GAMMA-SOFT NUCLEI[1]

Y. Alhassid,[2] G. F. Bertsch,[3] D. J. Dean, S. E. Koonin[4]

Shell-model Monte Carlo calculations for nuclei in the full major shell 50-82 are presented for both protons and neutrons. For the interaction, a pairing plus quadrupole is used, which is derived from a surface-peaked separable force. The methods are illustrated for ^{124}Sn, ^{128}Te, and ^{124}Xe. Shape distributions, moments of inertia, and pairing correlations are calculated as functions of temperature and angular velocity. The calculations are the first microscopic evidence of gamma softness of nuclei in this region.

1. Abstract of published paper: *Phys. Rev. Lett.* **77**, 1444 (1996).
2. Yale University, New Haven, CT.
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4. California Institute of Technology, Pasadena.

TEMPERATURE DEPENDENCE OF PAIR CORRELATIONS IN NUCLEI IN THE IRON REGION[1]

K. Langanke,[2] D. J. Dean, P. B. Radha,[2] S. E. Koonin[2]

The shell-model Monte Carlo approach is used to study thermal properties and pair correlations in ^{54,56,58}Fe and in ^{56}Cr. The calculations are performed with the modified Kuo-Brown interaction in the complete 1p-0f model space. Generally, it is found that the proton-proton and neutron-neutron J=0 pairing correlations, which dominate the ground-state properties of even-even nuclei, vanish at temperatures around 1 MeV. This pairing phase transition is accompanied by a rapid increase in the moment of inertia and a partial unquenching of the M1 strength. It is found that the M1 strength totally unquenches at higher temperatures, related to the vanishing of isoscalar proton-neutron correlations, which persist to higher temperatures than the pairing between like nucleons. The Gamow-Teller strength is also correlated to the isoscalar proton-neutron pairing and hence also unquenches at a temperature larger than that of the pairing phase transition.

1. Abstract of published paper: *Nucl. Phys. A* **602**, 244 (1996).
2. California Institute of Technology, Pasadena.

SMMC METHOD FOR TWO-NEUTRINO DOUBLE BETA DECAY[1]

P. B. Radha,[2] D. J. Dean, S. E. Koonin,[2] T.T.S. Kuo,[3] K. Langanke,[2] A. Poves,[4] J. Retamosa,[4] P. Vogel[2]

Shell-model Monte Carlo (SMMC) techniques are used to calculate two-neutrino double beta decay matrix elements. The approach against direct diagonalization for ^{48}Ca in the complete pf-shell using the KB3 interaction is validated. The method is then applied to the decay of ^{76}Ge in the $(0f_{5/2},1p,0g_{9/2})$ model space using a newly calculated realistic interaction. The result for the matrix element is 0.13 ± 0.05 MeV^{-1}, in reasonable agreement with the experimental value.

1. Abstract of published paper: *Phys. Rev. Lett.* **76**, 2642 (1996).
2. California Institute of Technology, Pasadena.
3. State University of New York at Stony Brook.
4. Universidad Autónoma de Madrid, Spain.

SHELL-MODEL MONTE CARLO CALCULATIONS NEAR N = Z (Ref. 1)

D. J. Dean

The pairing and structure of nuclei near N = Z is described in the framework of shell-model Monte Carlo (SMMC) calculations. Principal results include the enhancement of J=0, T=1 proton-neutron pairing at N=Z nuclei, and the marked difference of thermal properties between even-even and odd-odd N=Z nuclei. Additionally, studies are presented of the rotational properties of the T=1 (ground state), and T=0 band mixing seen in ^{74}Rb.

1. Abstract of invited paper to be published in Proceedings of Conference on Nuclear Structure at the Limits, Argonne, IL, July 22-26, 1996.

PAIRING CORRELATIONS IN N ~ Z pf-SHELL NUCLEI[1]

K. Langanke,[2] D. J. Dean, S. E. Koonin,[2] P. B. Radha[2]

Shell-model Monte Carlo calculations are performed to study pair correlations in the ground states of N=Z nuclei with masses A = 48-60. It is found that T=1, $J^\pi=0^+$ proton-neutron correlations play an important, and even dominant, role in the ground states of odd-odd N=Z nuclei, in agreement with experiment. By studying pairing in the ground states of $^{52-58}Fe$, it is observed that the isovector proton-neutron correlations decrease rapidly with increasing neutron excess. In contrast, both the proton, and trivially the neutron, correlations increase as neutrons are added. Thermal properties and the temperature dependence of pair correlations for ^{50}Mn and ^{52}Fe are also studied as exemplars of odd-odd and even-even N=Z nuclei. While for ^{52}Fe, results are similar to those obtained for other even-even nuclei in this mass range, the properties of ^{50}Mn at low temperatures are strongly influenced by isovector neutron-proton pairing. In coexistence with these isovector pair correlations, calculations also indicate an excess of isoscalar proton-neutron pairing over the mean-field values. The isovector neutron-proton correlations rapidly decrease with temperatures and vanish for temperatures above T = 700 keV, while the isovector correlations among like nucleons persist to higher temperatures. Related to the quenching of the isovector proton-neutron correlations, the average isospin decreases from 1 (appropriate for the ground state) to 0 as the temperature increases.

1. Abstract of paper to be published in *Nuclear Physics A*.
2. California Institute of Technology, Pasadena.

THE SPIN-DEPENDENT NEUTRALINO-NUCLEUS FORM FACTOR FOR ^{127}I (Ref. 1)

M. T. Ressell[2] *and D. J. Dean*

The results of detailed nuclear shell-model calculations of the spin-dependent elastic form factor for the nucleus ^{127}I are presented. The calculations were performed in extremely large model spaces which adequately describe the configuration mixing in this nucleus. Good agreement between the calculated and experimental values of the magnetic moment are found. Other nuclear observables are also compared to experiment. The dependence of the form factor upon the model space and effective interaction is discussed.

1. Abstract of paper to be published in Proceedings of International Workshop on the Identification of Dark Matter, Sheffield, England, September 8-12, 1996.
2. California Institute of Technology, Pasadena.

SHELL-MODEL MONTE CARLO METHODS[1]

S. E. Koonin[2] *and D. J. Dean*

Quantum Monte Carlo methods for dealing with large shell-model problems are reviewed. These methods reduce the imaginary-time, many-body evolution operator to a coherent superposition of one-body evolutions in fluctuating one-body fields; the resultant path integral is evaluated stochastically. First discussed is the motivation, formalism, and implementation of such shell-model Monte Carlo (SMMC) methods. There then follows a sampler of results and insights obtained from a number of applications. These include the ground-state and thermal properties of pf-shell nuclei, the thermal behavior of γ-soft nuclei, and the calculation of double beta-decay matrix elements. Finally, prospects for further progress in such calculations are discussed.

1. Abstract of paper to be published in Proceedings of Contemporary Shell Model Workshop, Philadelphia, PA, April 29-30, 1996.
2. California Institute of Technology, Pasadena.

A NEW MICROSCOPIC VIEW OF NUCLEAR DEFORMATION[1]

Z.-P. Li,[2] M. W. Guidry,[3] C.-L. Wu,[4] D. H. Feng[5]

The microscopic origin of deformation for heavy nuclei is discussed. Evidence is presented that the systematic features of nuclear deformation are determined primarily by filling of the normal parity shell-model orbitals of the valence shells, and that the abnormal parity orbitals play crucial but subsidiary roles. This is in accord with the point of view underlying the fermion dynamical symmetry model. In addition, it is demonstrated that the deformation systematics of the FDSM are consistent with those of the Nilsson model, despite their very different starting points, and that the assumptions of the FDSM are consistent with the assertion that the n-p quadrupole-quadrupole residual interaction is the essential reason for deformation. Finally, application of the same principles to superdeformation suggests that abnormal parity orbitals have a much more direct influence on superdeformation than on normal deformation.

1. Abstract of published paper: *Int. J. Mod. Physics E* **3**, 1119 (1994).
2. University of Tennessee, Knoxville.
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4. JIHIR guest from Chung Yuan Christian University, Chung-li, Taiwan, ROC.
5. Drexel University, Philadelphia, PA.

THE DYNAMICAL PAULI EFFECT[1]

M. W. Guidry,[2] C.-L. Wu,[3] D. H. Feng[4]

The dynamical Pauli effect of the fermion dynamical symmetry model is reviewed. It is concluded that there is strong empirical evidence from a variety of observations in support of this effect, and we propose new experiments that can test its pervasiveness. It is suggested that the dynamical Pauli effect is a fundamental principle of many-body physics that unifies many well-known but seemingly independent properties of collective nuclear systems. It is argued that there is a direct link between the dynamical Pauli effect and the appearance of gaps in the deformed single-particle spectrum such as the ones found at nucleon numbers 98 and 152 at normal deformation, and nucleon number 64 in superdeformation. Thus it is proposed that the dynamical Pauli effect may provide a simple, microscopic, and quantitative explanation for the appearance of many such gaps.

1. Abstract of published paper: *Ann. Phys.* **242**, 135 (1995).
2. Adjunct staff member from University of Tennessee, Knoxville.
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THE PROJECTED SHELL MODEL AND ITS NEWEST APPLICATIONS TO HIGH-SPIN SPECTROSCOPY[1]

Y. Sun,[2] J.-Y. Zhang,[3] M. W. Guidry,[4] D. H. Feng[5]

The projected shell model is a shell model developed for medium to heavy nuclear systems. It was primarily designed to study nuclear structure of high-spin states in normally deformed systems, and has recently been generalized to describe superdeformed bands. The model is expected to be a powerful tool for studying the physics related to the new gamma-ray detectors such as Gammasphere, Eurogam, and GASP. A general introduction to the model is given and three topics are discussed: 1) a systematic calculation and

a statistical comparison with the cranked shell model in treating rotational nuclei; 2) application to superdeformed bands; 3) the potential existence of $\Delta I = 4$ bifurcation in the PSM.

1. Abstract of invited paper presented at the XIX Symposium on Nuclear Physics, Oaxtepec, Mexico, January 3-6, 1996, to be published in *Revista Mexicana de Fisica.*
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$\Delta I=4$ BIFURCATION WITHOUT EXPLICIT FOUR-FOLD SYMMETRY[1]

Y. Sun,[2] J.-Y. Zhang,[3] M. W. Guidry[4]

It is demonstrated that $\Delta I=4$ bifurfaction can arise from the projected shell model without introducing explicitly either a Y_{44} deformation or an I^4 term in the Hamiltonian. If band mixing through the usual two-body Hamiltonian is dominated by a single two-band mixture near the yrast line, a clear staggering can appear. Detailed investigation shows that this staggering is associated with interference effects in the rotation from intrinsic to laboratory coordinate systems.

1. Abstract of published paper: *Phys. Rev. Lett.* **75**, 3398 (1995).
2. JIHIR guest from University of Tennessee, Knoxville.
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UNIVERSALITY OF SYMMETRY AND MIXED-SYMMETRY COLLECTIVE NUCLEAR STATES[1]

B. H. Smith,[2] X.-W. Pan,[2] D. H. Feng,[2] M. W. Guidry[3]

The global correlation in the observed variation with mass number of the E2 summed M1 transition strengths is examined for rare-earth nuclei. It is shown that a theory of correlated S and D fermion pairs with a simple pairing plus quadrupole interaction leads naturally to this universality. Thus a unified and quantitative description emerges for low-lying quadrupole and dipole strengths.

1. Abstract of published paper: *Phys. Rev. Lett.* **75**, 3086 (1995).
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UNIFIED DESCRIPTION OF SUPERDEFORMED BANDS IN EVEN AND ODD NUCLEI FOR THE MASS-130 REGION[1]

Y. Sun,[2] M. W. Guidry,[3] J.-Y. Zhang,[4] C.-L. Wu[5]

It is shown that the projected shell model can provide a unified description of yrast superdeformed bands in even- and odd-mass~130 nuclei. Anomalies in the dynamical moments of inertia observed in $^{133-136}$Nd can be understood within the theory. The calculated gamma-ray energies of the superdeformed states agree well with those for which the linking transitions have been measured, and spins for those states are predicted

where spins are not unambiguously assigned from experiment. Predictions are made also for superdeformed states in ^{132}Nd, where no data are yet available.

1. Abstract of paper submitted for publication in *Physics Letters B.*
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Z=110-111 ISOTOPES AND THE STABILITY OF HEAVY AND SUPERHEAVY ELEMENTS[1]

C.-L. Wu,[2] M. W. Guidry,[3] D. H. Feng[4]

The recent discovery of isotopes with Z = 110-111 suggests evidence for 1) a monopole-monopole interaction that does not appear explicitly in Nilsson-Strutinsky mass systematics, and 2) a competition between SU(2) and SU(3) dynamical symmetries that has been predicted for this region. Calculations suggest that these new isotopes are near-spherical, and may represent a true island of superheavy nuclei, but shifted downward in neutron number by these new physical effects.

1. Abstract of paper to be published in *Physics Letters B.*
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4. Drexel University, Philadelphia, PA.

SOLUTION OF THE NUCLEAR SHELL MODEL BY SYMMETRY-DICTATED TRUNCATION[1]

M. W. Guidry,[2] C.-L. Wu,[3] D. H. Feng[4]

The dynamical symmetries of the fermion dynamical symmetry model are used as a principle of truncation for the spherical shell model. Utilizing the usual principle of energy-dictated truncation to select a valence space, and symmetry-dictated truncation to select a collective subspace of that valence space, the full shell-model space can be reduced to one of manageable dimensions with modern supercomputers, even for the heaviest nuclei. The resulting shell model then consists of diagonalizing an effective Hamiltonian within the restricted subspace. This theory is not confined to any symmetry limits, and represents a full solution of the original shell model if the appropriate effective interaction of the truncated space can be determined. As a first step in constructing that interaction, an empirical determination is presented of its matrix elements for the collective subspace with no broken pairs in a representative set of nuclei within the mass range 130-250. It is demonstrated that this effective interaction can be parameterized in terms of a few quantities varying slowly with particle number, and is capable of describing a broad range of low-energy observables for these nuclei. Finally, a brief discussion is given of extending these methods to include a single broken collective pair.

1. Abstract of paper to be published in *Journal of Physics G.*
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4. Drexel University, Philadelphia, PA.

A SYSTEMATIC DESCRIPTION OF YRAST SUPERDEFORMED BANDS IN THE EVEN-EVEN MASS-190 REGION[1]

Y. Sun,[2] J.-Y. Zhang,[3] M. W. Guidry[4]

Yrast superdeformed bands for the even-even mass-190 region are described by the projected shell model. Excellent agreement with available data for all isotopes is obtained. Calculation of electromagnetic properties and pairing correlations provides a microscopic understanding of the observed gradual increase of dynamical moments of inertia with angular momentum in this mass region, and suggests that for superdeformation it is not very meaningful to distinguish between Coriolis anti-pairing and gradual high-j orbital alignment.

1. Abstract of paper submitted for publication in *Physical Review Letters.*
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QUANTITATIVE DESCRIPTION OF SUPERDEFORMED BANDS WITH THE PROJECTED SHELL MODEL[1]

Y. Sun[2] and M. W. Guidry[3]

A theoretical description of superdeformed bands based on the projected shell model is proposed. The shell model basis is constructed at the superdeformed minimum and projected onto states of good angular momentum, and a two-body Hamiltonian is then diagonalized in this basis. The superdeformed band in ^{132}Ce is taken as an example. Good agreement with the measured gamma-ray energies allows the suggestion of spin values for these superdeformed states. Finally, an explanation is proposed for the recently observed $\Delta I=4$ bifurcation disappearance at a rotational frequency of $\omega = 0.65$ in this nucleus.

1. Abstract of published paper: *Phys. Rev. C* **52**, 2844 (1995).
2. JIHIR guest from University of Tennessee, Knoxville.
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OPTIMAL CONDITIONS FOR THE OBSERVATION OF ΔI=4 BIFURCATION[1]

Y. Sun,[2] J.-Y. Zhang,[3] M. W. Guidry[4]

A recently developed theory of $\Delta I=4$ bifurcation based on the projected shell model is used to investigate optimal situations for observing this effect. General criteria are presented based on physical considerations at normal and superdeformation, and support these with calculations for selected cases. A set of nuclei is identified that may represent favorable cases for observation of this effect in normally deformed nuclei. It is found that the occurrence of $\Delta I=4$ bifurcation is extremely sensitive to the quasiparticle distribution near the Fermi surface; therefore such effects probe the microscopic structure of the observed rotational bands.

1. Abstract of paper to be published in *Physical Review C.*
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ALGEBRAIC METHODS IN THE NUCLEAR SHELL MODEL[1]

D. H. Feng,[2] X.-W. Pan,[2] M. W. Guidry[3]

Algebraic methods are illustrated in the nuclear shell model through a concrete example, the fermion dynamical symmetry model (FDSM). This model will be used to introduce important concepts such as dynamical symmetry, symmetry breaking, effective symmetry, and diagonalization within a higher symmetry basis.

1. Abstract of book chapter to be published in *Contemporary Nuclear Shell Models*, Springer-Verlag.
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PROPERTIES OF ΔI=4 BIFURCATION FROM THE PROJECTED SHELL MODEL[1]

Y. Sun,[2] J.-Y. Zhang,[3] M. W. Guidry[4]

A recent understanding of ΔI=4 bifurcation (or, ΔI=2 staggering) based on the projected shell model is used to investigate optimal situations for observing this effect. A set of nuclei is proposed that may represent favorable cases for observation of this effect in normally deformed nuclei. It is found that the occurrence of ΔI=4 bifurcation is extremely sensitive to the quasiparticle distribution near the Fermi surface; therefore such effects probe the microscopic quasiparticle structure of rotational bands in a very sensitive manner.

1. Abstract of paper to be published in *Physical Review C*.
2. JIHIR guest from University of Tennessee, Knoxville.
3. University of Tennessee, Knoxville.
4. Adjunct staff member from University of Tennessee, Knoxville.

ΔI=4 BIFURCATION: ORIGINS AND CRITERIA[1]

J.-Y. Zhang,[2] Y. Sun,[3] M. W. Guidry[4]

An alternative approach for the ΔI=4 bifurcation phenomenon has been further presented without introducing either a Y_{44} deformation or an I^4 term in the Hamiltonian explicitly. The optimal criteria for observing the phenomenon have been discussed as well.

1. Abstract of published paper: p. 68 in *Proceedings of 3rd Symposium on Joint Spectroscopy Experiments Utilizing JAERI Tandem-Booster, Tokai, Japan, July 27-28, 1995* (JAERI-Conf 96-007, 1996).
2. University of Tennessee, Knoxville.
3. JIHIR guest from University of Tennessee, Knoxville.
4. Adjunct staff member from University of Tennessee, Knoxville.

PROJECTED SHELL-MODEL AND HIGH-SPIN SPECTROSCOPY[1]

K. Hara[2] and Y. Sun[3]

Most of the nuclei in the nuclear chart are deformed except for those in the vicinity of the magic numbers. It is difficult to treat such nuclei within the framework of the standard (spherical) shell model. On the other hand, the necessity for a proper quantum mechanical treatment of high-spin states has been steadily growing ever since modern experimental techniques made it possible to measure the fine details of the high-spin states of heavy nuclei. The present article reviews an approach based on the angular momentum projection technique which was initiated in the late seventies for the purpose of carrying out shell-model configuration-mixing calculations efficiently. A large number of examples is presented with an emphasis on the physical interpretation of the numerical results. Computing time for the whole spectrum up to spin ≈ 40 of an axially symmetric rare-earth nucleus takes only a few minutes on a mainframe, showing the efficiency of the method. Most of the present calculations were carried out on a workstation, but computation on a modern PC also presents no problem, so that one can enjoy a genuine quantum mechanical analysis of high-spin data using a facility available everywhere. Detailed technical information which may be useful for programming purposes is given in an Appendix.

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1. Abstract of published paper: *Int. J. Mod. Phys. E* **4**, 637 (1995).
2. Technische Universität München, Germany.
3. JIHIR guest from University of Tennessee, Knoxville.

A REVIEW OF THE CURRENT EFFORTS OF THE PROJECTED SHELL MODEL IN NUCLEAR STRUCTURE PHYSICS[1]

D. H. Feng,[2] Y. Sun,[3] J.-Y. Zhang,[4] M. W. Guidry[5]

The projected shell model (PSM) of Hara and Sun is reviewed. This is a shell model developed for medium to heavy systems. Although the model can be applied to a variety of collective modes, its current numerical code is primarily designed to study nuclear structure of well-deformed systems in high and low spin states. A general discussion will be given of the model and its relationship with the algebraic approaches such as the fermion dynamical symmetry model, and also show various applications to the physics of high-spin spectroscopy, level statistics (or "quantum chaos"), and ΔI=4 bifurcation.

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1. Abstract of paper to be published in Proceedings of II International Symposium on Heavy-Ion Physics and Its Applications, Lanzhou, China, August 29 - September 1, 1995.
2. Drexel University, Philadelphia, PA.
3. JIHIR guest from University of Tennessee, Knoxville.
4. University of Tennessee, Knoxville.
5. Adjunct staff member from University of Tennessee, Knoxville.

STATISTICAL DISTRIBUTION OF INERTIAL PARAMETERS IN NORMALLY DEFORMED NUCLEI[1]

J.-Y. Zhang,[2] Y. Sun,[3] M. W. Guidry,[4] D. H. Feng[5]

A systematic comparison of data and theory is presented for the statistical distribution of low-spin inertial parameters in normally deformed nuclei. In a comparison with 2145 measured yrast-band pairs in even-even nuclei, it is found that the distributions in average absolute difference for both the kinematic moment of inertia $J^{(1)}$ and the dynamical moment of inertia $J^{(2)}$ are well reproduced by the projected shell model, but not by the usual cranking model with particle number projection. Some physical implications of these results are discussed.

1. Abstract of published paper: *Phys. Rev. C* **52**, 2330 (1995).
2. University of Tennessee, Knoxville.
3. JIHIR guest from University of Tennessee, Knoxville.
4. Adjunct staff member from University of Tennessee, Knoxville.

E3 TRANSITION PROBABILITIES IN THE PLATINUM, MERCURY, AND LEAD ISOTOPES[1]

J. L. Egido,[2] V. Martin,[3] L. M. Robledo,[2] Y. Sun[4]

Spectroscopical properties of the platinum, mercury, and lead isotopes are studied within the Hartree-Fock plus BCS framework with the finite range density-dependent Gogny force. These properties are also studied beyond mean-field theory by combining the use of generator-coordinate-method-like wave functions with the angular momentum projection technique as to generate many-body correlated wave functions that are at the same time eigenstates of the angular momentum operator. This formalism is applied to the calculation of reduced transition probabilities B(E3) from the lowest-lying octupole collective state to the ground state of several isotopes of the platinum, mercury, and lead nuclei whose experimental B(E3) values present a peculiar behavior. The projected calculations show a large improvement over the unprojected ones when compared with the experimental data. The unprojected calculations are unable to predict any structure in the B(E3).

1. Abstract of published paper: *Phys. Rev. C* **53**, 2855 (1996).
2. Universidad Autónoma de Madrid, Spain.
3. Universidad Politécnica de Madrid, Spain.
4. JIHIR guest from University of Tennessee, Knoxville.

MULTIPLE DIPOLE BANDS AT PROLATE SHAPES IN ^{136}Nd AND THEIR DESCRIPTION THROUGH THE PROJECTED SHELL MODEL[1]

*C. M. Petrache,[2] Y. Sun,[3] D. Bazzacco,[2] S. Lunardi,[2] C. Rossi Alvarez,[2] R. Venturelli,[2]
D. De Acuña,[4] G. Maron,[4] M. N. Rao,[2] Z. Podolyak,[2] J.R.B. Oliveira[5]*

Five bands dominated by strong M1 transitions have been observed in the ^{136}Nd nucleus. Two of them consist of only dipole transitions, whereas the other three show also weak crossover transitions. The bands have been firmly connected to lower-spin states. Theoretical calculations using the projected shell model suggest quasiparticle configurations involving two protons and two neutrons for the four lowest-lying bands.

1. Abstract of published paper: *Phys. Rev. C* **53**, 2581 (1996).
2. INFN, Padova, Italy.
3. JIHIR guest from University of Tennessee, Knoxville.
4. INFN, Legnaro, Italy.
5. Universidade de São Paulo, Brazil.

VARIED SIGNATURE SPLITTING PHENOMENA IN ODD PROTON NUCLEI[1]

Y. Sun,[2] D. H. Feng,[3] S. Wen[4]

Varied signature splitting phenomena in odd proton rare-earth nuclei are investigated. Signature splitting as functions of K and j in the angular momentum projection theory is explicitly shown and compared with those of the particle rotor model. The observed deviations from these rules are due to the band mixings. The recently measured ^{169}Ta high-spin data are taken as a typical example where fruitful information about signature effects can be extracted. Six bands, two of which have not yet been observed, were calculated and discussed in detail in this paper. The experimentally unknown bandhead energies are given.

1. Abstract of published paper: *Phys. Rev. C* **50**, 2351 (1994).
2. JIHIR guest from University of Tennessee, Knoxville.
3. Drexel University, Philadelphia, PA.
4. China Institute of Atomic Energy, Beijing, PRC.

ROTATIONAL STRUCTURES IN ^{177}Ta (Ref. 1)

*D. E. Archer,[2] M. A. Riley,[2] T. B. Brown,[2] J. Döring,[2] D. J. Hartley,[2] G. D. Johns,[2]
T. D. Johnson,[2] R. A. Kaye,[2] J. Pfohl,[2] S. L. Tabor,[2] J. Simpson,[3] Y. Sun[4]*

High-spin states in ^{177}Ta were produced using the ^{170}Er(^{11}B,4n) reaction at 55 and 60 MeV. Considerable extensions have been made to the previously known level scheme, and new structures have been found. B(M1)/B(E2) ratios have been extracted for strongly coupled bands. The behavior of the different rotational cascades, in particular the anomalous crossing frequency observed in the [541]1/2$^-$ proton $h_{9/2}$ band and the occurrence of "identical bands," is discussed. Comparisons are made with projected shell-model calculations.

1. Abstract of published paper: *Phys. Rev. C* **52**, 1326 (1995).
2. Florida State University, Tallahassee.
3. Daresbury Laboratory, Warrington, England.
4. JIHIR guest from University of Tennessee, Knoxville.

COMPUTATIONAL PHYSICS

BASIS SPLINE COLLOCATION METHOD FOR SOLVING THE SCHRÖDINGER EQUATION IN AXILLARY SYMMETRIC SYSTEMS[1]

D. R. Kegley Jr.,[2] V. E. Oberacker,[3] M. R. Strayer, A. S. Umar,[2] J. C. Wells[4]

Basis spline collocation is used to solve the Schrödinger equation on a lattice for axially symmetric systems, with and without spin. The focus of the present work is on systems which have continuum states, weakly bound states, or strong spin-orbit coupling, since these are the most difficult to solve on the lattice. A brief overview of the basis spline collocation method is included which concentrates primarily on those aspects of the theory which are relevant to its application in cylindrical coordinates. To demonstrate the method, we solve several model problems selected from the fields of atomic and nuclear physics.

1. Abstract of published paper: *J. Comput. Phys.* **128**, 197 (1996).
2. Vanderbilt University, Nashville, TN.
3. Consultant from Vanderbilt University, Nashville, TN.
4. Consultant from Harvard-Smithsonian Center for Astrophysics, Cambridge, MA.

CONVERGENCE OF A LATTICE CALCULATION FOR BOUND-FREE MUON-PAIR PRODUCTION IN PERIPHERAL RELATIVISTIC HEAVY-ION COLLISIONS[1]

J. C. Wells,[2] V. E. Oberacker,[3] M. R. Strayer, A. S. Umar[4]

A nonperturbative treatment has been developed for bound-free lepton-pair production caused by the strong and sharply pulsed electromagnetic fields generated by heavy ions in peripheral, relativistic collisions based on the solution of the time-dependent Dirac equation using lattice techniques. In this paper, refinements and extensions of numerical methods for this problem are discussed, and convergent calculations are demonstrated, with respect to the parameters of the lattice, for bound-free muon-pair production in collisions near grazing incidence of $^{238}U^{92+}$ and beam kinetic energies of 30 GeV per nucleon in the fixed-target frame.

1. Abstract of published paper: *Phys. Rev. A* **53**, 1498 (1996).
2. Consultant from Harvard-Smithsonian Center for Astrophysics, Cambridge, MA.
3. Consultant from Vanderbilt University, Nashville, TN.
4. Vanderbilt University, Nashville, TN.

PARALLEL IMPLEMENTATION OF MANY-BODY MEAN-FIELD EQUATIONS[1]

C. R. Chinn,[2] A. S. Umar,[2] M. Vallières,[3] M. R. Strayer

Numerical methods are described which are used to solve the system of stiff, nonlinear partial differential equations resulting from the Hartree-Fock description of many-particle quantum systems, as applied to the structure of the nucleus. The solutions are performed on a three-dimensional Cartesian lattice. Discretization is achieved through the lattice basis-spline collocation method, in which quantum-state vectors and coordinate-space operators are expressed in terms of basis-spline functions on a spatial lattice. All numerical procedures reduce to a series of matrix-vector multiplications and other elementary operations, which are performed on a number of different computing architectures, including the Intel Paragon and the Intel iPSC/860 hypercube. Parallelization is achieved through a combination of mechanisms employing the Gram-Schmidt procedure, broadcasts, global operations, and domain decomposition of state vectors. The approach to the problems of limited node memory and node-to-node communication overhead inherent in using distributed-memory, multiple-instruction, multiple-data stream parallel computers is discussed. An algorithm was developed to reduce the communication overhead by pipelining some of the message-passing procedures.

1. Abstract of published paper: *Phys. Rev. E* **50**, 5096 (1994).
2. Vanderbilt University, Nashville, TN.
3. Drexel University, Philadelphia, PA.

COMPUTATIONAL TECHNIQUES[1]

D. R. Schultz and M. R. Strayer

Essential to all fields of physics is the ability to perform numerical computations accurately and efficiently. Whether the specific approach involves perturbation theory, close coupling expansion, solution of classical equations of motion, or fitting and smoothing of data, basic computational techniques such as integration, differentiation, interpolation, matrix and eigenvalue manipulation, Monte Carlo sampling, and solution of differential equations must be among the standard tool kit. This chapter outlines a portion of this tool kit with the aim of giving guidance and organization to a wide array of computational techniques.

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1. Abstract of published paper: *pp. 104-119 in Atomic, Molecular, & Optical Physics Handbook,* AIP Press, Woodbury, NY, 1996.

HYPERSPHERICAL THEORY OF THREE-PARTICLE FRAGMENTATION AND WANNIER'S THRESHOLD LAW[1]

J. H. Macek[2] *and S. Y. Ovchinnikov*[3]

A representation of three-particle wave functions, well adapted to computations of low-energy fragmentation states of systems interacting electrostatically, is derived. A basis, called an angle-Sturmian basis, is introduced. Exact wave functions are represented by sums over the angle-Sturmian functions and integrals over the index of Bessel functions. Equations for the coefficients of the Sturmian functions are derived. Solutions of these equations are given in the approximation that one Sturmian is employed. Integral representations of the approximate three-particle wave functions are obtained. Evaluation of the integral for large hyper-radius R gives the hidden-crossing theory, familiar from representations of ion-atom interactions at low energy. It is shown that ionization components emerge simply only for complex values of R. Such components conform to Wannier's threshold law.

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1. Abstract of published paper: *Phys. Rev. A* **54**, 544 (1996).
2. UT-ORNL Distinguished Scientist.
3. Guest assignee from University of Tennessee, Knoxville.

6. COMPILATIONS AND EVALUATIONS

OVERVIEW

The Physics Division operates the Nuclear Data Project. The Nuclear Data Project supports the national program in nuclear structure data evaluation. This organization also participates in an international network of data centers.

NUCLEAR DATA PROJECT

Y. A. Akovali,[1] *A. Artna-Cohen,*[2] *J. Huo,*[3] *H.-Q. Jin,*[4]
M. R. Lay, M. J. Martin, S. Rab,[5] *and M. R. Schmorak*[6]

The Nuclear Data Project (NDP) is one of five data evaluation centers comprising the U.S. Nuclear Data Network (USNDN). The Project is responsible for the evaluation of nuclear structure information in the mass region A ≥ 199. The NDP maintains a complete computer-indexed library of reports and published articles in experimental nuclear structure physics as well as copies of the Evaluated Nuclear Structure Data and Nuclear Structure Reference files (ENSDF, NSR).

The Editor-in-Chief of the *Nuclear Data Sheets* is a member of the Nuclear Data Project staff. All mass chains from the 15 centers in the International Nuclear Data Network are edited here, and the Editor-in-Chief has the ultimate responsibility for the quality of the mass chains entered into ENSDF and, thus, for what is published in the *Nuclear Data Sheets*.

Data Evaluation. During this report period, NDP staff members prepared revised evaluations for the A = 133, 152, 200, 202, 204, 214, 216, 218, 222, 224, 226, 228, and 237 mass chains. These evaluations have been published or are in press in the *Nuclear Data Sheets*.

Mass Chain Editing and Review. NDP staff members edited and/or reviewed 27 mass chains.

Information Services. NDP staff members responded to requests for specific information by researchers outside the evaluation center. Responses took the form of searches of the ENSDF and NSR files and personal consultation. A list of reports and preprints received by the NDP is prepared and distributed monthly to division staff members.

Database Development. For FY95 and continuing, the NDP supports a 0.5 FTE effort in work on the division's Nuclear Structure Database (NSDB). The NDP contribution has focussed on entering nuclear structure data for nuclides with Z = 62 - 75 and A = 155 - 185, and on linking the NSDB with ENSDF.

Other Activities. The data for alpha decay from all even-even nuclides have been reviewed, and recommended values for the radius parameter have been obtained. These parameters form the basis for calculating the alpha-decay hindrance factors for the odd and odd-odd nuclides. A file of these parameters, along with the evaluated input data, will be maintained on-line at BNL. See abstract at the end of this section.

Research. NDP staff members have participated in research with other groups in the division. Discussion of these activities may be found in the research section of this report.

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1. Through FY95. Funding transferred to research section for FY96.
2. Consultant.
3. Guest assignee from Jilin University, PRC, for summer 1995.
4. ORNL Postdoctoral Associate, Oak Ridge Institute for Science and Education, 0.5 FTE for FY96 through March 1996.
5. Consultant through March 1996.
6. Consultant through FY 1995.

ABSTRACTS OF PAPERS PUBLISHED OR SUBMITTED FOR PUBLICATION

COMPILATIONS AND EVALUATIONS

REVIEW OF ALPHA-DECAY DATA FROM DOUBLY-EVEN NUCLEI[1]

Y. A. Akovali

Alpha-decay data from doubly-even nuclei throughout the periodic table are reviewed and evaluated. From these data, nuclear radius parameters are calculated by using the Preston formula for α-decay probabilities. The radius parameters for each element behave rather regularly as a function of neutron number. They show minima at the major closed shells, increase sharply for parents just above the closed shells, and decrease smoothly toward the next shell closure. The same trend is observed for α reduced widths calculated using the Rasmussen formalism. Any irregularity or large departure from this behavior indicates probable incorrect input data. This systematic behavior can also be utilized to estimate partial half-lives.

ORNL-DWG 96M-6983

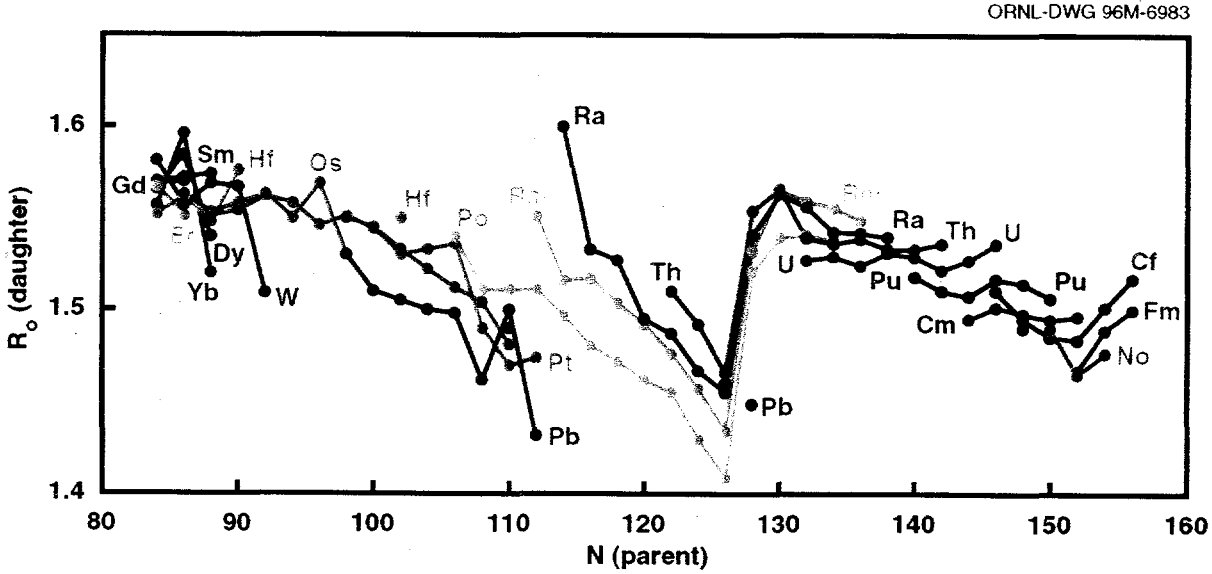

Fig. 6.1. The nuclear radius parameters of α daughters for doubly-even nuclei.

1. Abstract of paper to be published in Proceedings of the Ninth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Budapest, Hungary, October 8-12, 1996.

7. PUBLICATIONS

List Prepared by Shirley J. Ball

OVERVIEW

The following list of publications includes primarily those articles by Physics Division staff members and associates which appeared in print from October 1994 through September 1996. Articles pending publication as of September 30, 1996, are listed at the end of the section.

Akovali, Y. A.
"Nuclear Data Sheets for A = 241," *Nucl. Data Sheets* **76**, 127-90 (Sept. 1995)

Akovali, Y. A.
"Nuclear Data Sheets for A = 222," *Nucl. Data Sheets* **77**, 271-98 (1996)

Albrecht, R., V. Antonenko, T. C. Awes, C. Barlag, F. Berger, M. A. Bloomer, C. Blume, D. Bock, R. Bock, E. M. Bohne, D. Bucher, A. Claussen, G. Clewing, R. Debbe, L. Dragon, A. Eklund, S. Fokin, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, O. Hansen, G. Hoelker, J. Idh, M. Ippolitov, P. Jacobs, K. H. Kampert, K. Karadjev, B. W. Kolb, A. Lebedev, H. Loehner, I. Lund, V. Manko, B. Moskowitz, S. Nikolaev, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, F. Plasil, A. M. Poskanzer, M. Purschke, B. Roters, R. Santo, H. R. Schmidt, K. Soderstrom, S. P. Sorensen, P. Stankus, K. Steffens, P. Steinhaeuser, E. Stenlund, D. Stueken, A. Vinogradov, H. Wegner, and G. R. Young
"Production of η Mesons in 200 A GeV/c S+S and S+Au Reactions," *Phys. Lett. B* **361**, 14-20 (1995)

Albrecht, R., V. Antonenko, T. C. Awes, C. Barlag, F. Berger, M. Bloomer, C. Blume, D. Bock, R. Bock, E. M. Bohne, D. Bucher, G. Claesson, A. Claussen, G. Clewing, R. Debbe, L. Dragon, Yu. Dubovik, A. Eklund, S. Fokin, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, O. Hansen, G. Hoelker, J. Idh, M. Ippolitov, P. Jacobs, K. H. Kampert, K. Karadjev, B. W. Kolb, A. Lebedev, H. Loehner, I. Lund, V. Manko, B. Moskowitz, S. Nikolaev, J. Nystrand, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, B. Roters, S. Saini, R. Santo, H. Schlagheck, H. R. Schmidt, K. Soderstrom, S. P. Sorensen, P. W. Stankus, K. Steffens, P. Steinhaeuser, E. Stenlund, D. Stueken, A. Vinogradov, H. Wegner, and G. R. Young
"Limits on the Production of Direct Photons in 200 A GeV ^{32}S+Au Collisions," *Phys. Rev. Lett.* **76**, 3506-09 (May 1996)

Alhassid, Y., G. F. Bertsch, D. J. Dean, and S. E. Koonin
"Shell-Model Monte-Carlo Studies of γ-Soft Nuclei," *Phys. Rev. Lett.* **77**, 1444-47 (Aug. 1996)

Alton, G. D. (Invited Presentation)
"Ion Sources for Initial Use at the Holifield Radioactive Ion Beam Facility," Proceedings, Workshop on Postacceleration Issues at the ISL Laboratory, Berkeley, Calif., Oct. 27-29, 1993, *Particle Accelerators* **47**, 133-44 (1994)

Alton, G. D.
"Sources of Low-Charge-State Positive-Ion Beams," pp. 69 ff. in Atomic, Molecular, and Optical Physics: Charged Particles, Vol. 29A, Academic Press, New York, 1995

Alton, G. D.
"High Brightness Field Ionization and Field Evaporation (Liquid Metal) Ion Sources," pp. 239 ff. in Handbook of Ion Sources, CRC Press, New York, 1995

Alton, G. D. (Invited Presentation)
"Future Prospects for ECR Ion Sources with Improved Charge State Distributions," pp. 362-71 in Proceedings, 14th International Conference on Cyclotrons and Their Applications, Cape Town, South Africa, Oct. 8-13, 1995, World Scientific Publishing, Singapore, 1996

Alton, G. D.
"A Combined Thermal Dissociation and Electron Impact Ionization Source for RIB Generation," Proceedings, Sixth International Conference on Ion Sources, Whistler, B.C., Canada, Sept. 9-11, 1995, *Rev. Sci. Instrum.* **67**, 1626-29 (Apr. 1996)

Alton, G. D., J. Dellwo, H. K. Carter, J. Kormicki, G. di Bartolo, J. C. Batchelder, J. Breitenbach, J. A. Chediak, K. Kentoff-Nilsen, and S. Ichikawa (Invited Presentation)
"The Diffusion Properties of Ion Implanted Species in Selected Target Materials," pp. 1672 ff. in Proceedings, International Conference on Neutrons and Applications, Vol. 2339, Crete, Greece, June 12-18, 1994, International Society for Optical Engineering, 1995

Alton, G. D., J. Dellwo, R. F. Welton, and D. N. Smithe
"Computational Studies for an Advanced Design ECR Ion Source," pp. 1022 ff. In Proceedings, 1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995, IEEE, Piscataway, N.J., 1996

Alton, G. D., M. R. Dinehart, D. T. Dowling, D. L. Haynes, C. A. Irizarry, C. M. Jones, R. C. Juras, S. N. Lane, C. T. LeCroy, M. J. Meigs, G. D. Mills, S. W. Mosko, S. N. Murray, D. K. Olsen, and B. A. Tatum
"Oak Ridge 25URC Tandem Accelerator — 1992 SNEAP Lab Report," pp. 204-05 in Proceedings, Symposium of Northeastern Accelerator Personnel, Hull, Canada, Sept. 23-25, 1992, World Scientific Publishing, Singapore, 1995

Alton, G. D., M. R. Dinehart, D. T. Dowling, D. L. Haynes, C. M. Jones, R. C. Juras, S. N. Lane, C. T. LeCroy, M. J. Meigs, G. D. Mills, S. W. Mosko, S. N. Murray, D. K. Olsen, and B. A. Tatum
"Oak Ridge 25URC Tandem Accelerator — 1993 SNEAP Lab Report," pp. 283 ff in Proceedings, Symposium of Northeastern Accelerator Personnel, Rochester, NY, Sept. 22-26, 1993, World Scientific Publishing, Singapore, 1995

Alton, G. D., and G. D. Mills
"A High Efficiency Positive (Negative) Surface Ionization Source for RIB Generation," Proceedings, Sixth International Conference on Ion Sources, Whistler, B.C., Canada, Sept. 9-11, 1995, *Rev. Sci. Instrum.* 67, 1630-33 (Apr. 1996)

Alton, G. D., and D. N. Smithe (Invited Presentation)
"A Single-Frequency ECR Ion Source with a Large Uniformly Distributed Resonant Plasma Volume," pp. 100 ff. in Proceedings, Twelfth International Workshop on ECR Ion Sources, Wako-shi, Japan, Apr. 25-27, 1995, Report INS-J-182, Institute for Nuclear Study, Tokyo,1995

Alton, G. D., R. A. Sparrow, and R. E. Olson
"The Stripping Properties of a Plasma: Computational Studies," pp. 541-50 in Proceedings, The Second International Conference on Computational Physics (ICCP-2), Beijing, China, Sept. 13-17, 1993, International Press, Hong Kong, 1995

Andersson, L. R., and J. Burgdorfer (Invited Presentation)
"Radiative Processes in Atomic Collisions at Storage Rings," pp. 595-604 in Proceedings, XVIII International Conference the Physics of Electronic and Atomic Collisions, Aarhus, Denmark, July 21-27, 1993, AIP Conf. Proc. 295, American Institute of Physics, New York, 1993

Andersson, L. R., and J. Burgdorfer (Invited Presentation)
"Photoabsorption and Compton Scattering in Ionization of Helium at High Photon Energies," pp. 836-43 in Proceedings, XVIII International Conference on the Physics of Electronic and Atomic Collisions, Aarhus, Denmark, July 21-27, 1993, AIP Conf. Proc. 295, American Institute of Physics, New York, 1993

Andersson, L., and J. Burgdorfer
"Excitation–Ionization and Double Ionization of Helium by Compton Scattering," *Phys. Rev. A* **50**, R2810-13 (Oct. 1994)

Awes, T. C. (Invited Presentation)
"Investigation of Direct Photon Production in 200 A GeV S + Au Reactions," pp. 633-38 in QCD and High Energy Hadronic Interactions (Proceedings, XXIX Rencontre de Moriond, Meribel, France, Mar. 19-26, 1994), Editions Frontiers, Gif-sur-Yvette, France, 1994

Awes, T. C. (Invited Presentation)
"Search for Direct Photon Production in 200 A GeV S + Au Reactions: A Status Report," Proceedings, Eleventh International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter '95), Monterey, Calif., Jan. 9-13, 1995, *Nucl. Phys. A*590, 81c-91c (1995)

Awes, T. C., R. Albrecht, M. Bloomer, C. Blume, D. Bock, R. Bock, D. Bucher, G. Clewing, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, G. Hoelker, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, H. Loehner, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, F. Plasil, A. M. Poskanzer, M. Purschke, B. Roters, S. Saini, R. Santo, H. R. Schmidt, S. P. Sorensen, K. Steffens, P. Steinhaeuser, E. Stenlund, D. Stueken, and G. R. Young
"Bose-Einstein Correlations of Soft Pions in Ultrarelativistic Nucleus–Nucleus Collisions," *Z. Phys. C* **69**, 67-76 (Dec. 1995)

Awes, T. C., C. Barlag, F. Berger, M. A. Bloomer, C. Blume, D. Bock, R. Bock, E.-M. Bohne, D. Bucher, A. Claussen, G. Clewing, L. Dragon, A. Eklund, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, G. Hoelker, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, F. Plasil, A. M. Poskanzer, M. Purschke, B. Roters, R. Santo, H. R. Schmidt, S. P. Sorensen, K. Steffens, P. Steinhaeuser, E. Stenlund, D. Stueken, and G. R. Young
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"Atomic Collisions with 33-TeV Lead Ions," Proceedings, 8th International Conference on the Physics of Highly Charged Ions (HCI-96), Omiya, Japan, Sept. 23-26, 1996

Wang, X.-H., C.-H. Yu, D. M. Cullen, D. C. Bryan, M. Devlin, M. J. Fitch, A. Galindo-Urribari, R. W. Gray, D. M. Herrick, R. W. Ibbotson, K. Kurz, S. Mullins, S. Pilotte, D. C. Radford, M. R. Satteson, M. Simon, D. Ward, C. Y. Wu, and L. H. Yao
"High Spin States in Odd-Odd ^{164}Lu," *Physical Review C*

Wauters, J., J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, L. F. Conticchio, C. N. Davids, T. Davinson, R. J. Irvine, D. Seweryniak, K. S. Toth, W. B. Walters, P. J. Woods, and E. F. Zganjar
"Fine Structure in the α Decay of ^{189}Bi," *Physical Review C*

Welton, R. F., G. D. Alton, and S. N. Murray (Invited Presentation)
"Ionization Efficiency and Effusive Delay Time Characterization of High Temperature Target-Ion Sources for RIB Generation," Proceedings, 14th International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, Nov. 6-9, 1996

Wong, C. Y. (Invited Presentation)
"J/ψ and ψ' Suppression in High-Energy Heavy-Ion Collisions," Proceedings, Twelfth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter '96), Heidelberg, Germany, May 20-24, 1996

Wong, C. Y.
"Suppression of J/ψ and ψ' Production in High-Energy Pb on Pb Collisions," *Physical Review Letters*

Wong, C. Y., and L. Chatterjee (Invited Presentation)
"Effects of Final-State Interaction and Screening on Strange and Heavy Quark Production," Proceedings, Strangeness in Hadronic Matter Workshop, Budapest, Hungary, May 15-17, 1996, Heavy Ion Physics

Wong, C. Y., and L. Chatterjee
"Effects of Screening on Quark-Antiquark Cross Sections in Quark-Gluon Plasma," *Zeitschrift fuer Physik*

Wong, C. Y., and C. W. Wong
"Color-Octet Fraction in J/ψ Production," *Physical Review Letters*

Wu, C. Y., D. Cline, T. Czosnyka, A. Backlin, C. Baktash, R. M. Diamond, G. D. Dracoulis, L. Hasselgren, H. Kluge, B. Kotlinski, J. R. Leigh, J. O. Newton, W. R. Phillips, S. H. Sie, J. Srebrny, and F. S. Stephens
"Quadrupole Collectivity and Shapes of Os–Pt Nuclei," *Nuclear Physics A*

Wu, W., S. Datz, N. L. Jones, H. F. Krause, B. Rosner, K. D. Sorge, and C. R. Vane
"Quasi-Free Electron Process in the Single Ionization of He by Fast Protons," *Physical Review A*

Yan, Q., J. Burgdorfer, and F. W. Meyer
"A Case for Occupied Surface States Within the Band Gap of LiF (100)," *Physical Review Letters*

Yan, Q., and F. W. Meyer
"Electron Capture from Occupied Surface States within the Band Gap of LiF(100)," Proceedings, 13th International Conference on Defects in Insulating Materials, Winston-Salem, N.C., July 15-19, 1996, Trans. Tech. Publication Ltd. (Materials Science Forum)

Zhu, Y.-Y., M. Guidry, Z.-P. Li, and C.-L. Wu
"The Composite Particle Representation Theory and the Baryon Spectrum," *Physical Review D*

Zhang, J.-Y., Y. Sun, and M. W. Guidry
"$\Delta I = 4$ Bifurcation: Origins and Criteria," Proceedings, 3rd Workshop on Nuclear Spectroscopy by Use of JAERI Tandem Booster, Tokai, Japan, July 27-28, 1995

8. PAPERS PRESENTED AT SCIENTIFIC MEETINGS

List Prepared by Shirley J. Ball

OVERVIEW

A list of invited and contributed talks presented by Physics Division staff members and associates from October 1994 through September 1996 is given.

1994

European Research Conference on Particle–Solid Interaction, Sebastian, Spain, Oct. 1-6, 1994

Datz, S. (Invited Presentation)
"Differential Alignment of Excited Stated in Resonant Coherent Channeling Excitation"

1994 Symposium of Northeastern Accelerator Personnel, Kalamazoo, Mich., Oct. 12-15, 1994

Alton, G. D., M. R. Dinehart, D. T. Dowling, D. L. Haynes, C. M. Jones, R. C. Juras, S. N. Lane, C. T. Lecroy, M. J. Meigs, G. D. Mills, S. W. Mosko, S. N. Murray, D. K. Olsen, and B. A. Tatum
"Oak Ridge 25URC Tandem Accelerator"

Jones, N. L.
"Investigation of a New Type Charging Belt"

Jones, N. L.
"A Video Strip Chart Program"

Meigs, M. J., G. D. Alton, R. L. Auble, J. D. Bailey, J. Dellwo, M. R. Dinehart, D. T. Dowling, D. L. Haynes, C. M. Jones, R. C. Juras, S. N. Lane, C. T. Lecroy, G. D. Mills, S. W. Mosko, P. E. Mueller, S. N. Murray, D. K. Olsen, B. A. Tatum, and H. Wollnik
"Status Report on the Holifield Radioactive Ion Beam Project"

Meigs, M. J., C. M. Jones, R. C. Juras, and D. L. Haynes
"The 25URC Tandem Resistor-Based Voltage Grading System: Installation and First Operating Experience"

International Workshop on Structure and Dynamics of Quantum Many-Body Systems, Aizn, Japan, Oct. 19-21, 1994

Ormand, W. E. (Invited Presentation)
"Shell Model the Monte Carlo Way"

American Physical Society, Division of Nuclear Physics, Williamsburg, Va., Oct. 26-29, 1994

Cullen, D. M., C.-H. Yu, R. W. Gray, M. J. Fitch, X.-H. Wang, C. Baktash, N. R. Johnson, W. Reviol, A. O. Macchiavelli, and I. Y. Lee
"New High-Spin States in ^{171}Hf and ^{172}Hf," Bull. Am. Phys. Soc. **39**, 1410 (Oct. 1994)

Lund, B. J., N.P.T. Bateman, S. Utku, D. J. Horen, and G. R. Satchler
"Isospin Mixing of Transitions to the 2_1^+ and 3_1^- States of $^{90-96}$Zr," Bull. Am.Phys. Soc. **39**, 1393 (Oct. 1994)

Metlay, M. P., P. D. Cottle, J. D. Canterbury, J. L. Johnson, S. Raman, and C. W. Nestor, Jr.
"Are Octupole Vibrations Harmonic?," Bull. Am. Phys. Soc. **39**, 1420 (Oct. 1994)

Mueller, W. F., H.-Q. Jin, J. M. Lewis, W. Reviol, L. L. Riedinger, C.-H. Yu, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, and F. K. McGowan
"High Spin Studies in ^{181}Au," Bull. Am. Phys. Soc. **39**, 1419 (Oct. 1994)

Rupnik, D., E. F. Zganjar, J. L. Wood, P. B. Semmes, and W. Nazarewicz
"Coexisting Near-Prolate Triaxial Structures in ^{187}Au," Bull. Am. Phys. Soc. **39**, 1419 (Oct. 1994)

IEEE 1994 Nuclear Science Symposium and Medical Imaging Conference, Norfolk, Va., Oct. 30, 1994

Simpson, M. L., C. L. Britton, A. L. Wintenberg, and G. R. Young
"An Integrated, CMOS, Constant-Fraction Timing Discriminator for Multichannel Detector Systems"

Wintenberg, A. L., T. C. Awes, C. L. Britton, Jr., M. S. Emery, M. N. Ericson, F. Plasil, M. L. Simpson, J. W. Walker, and G. R. Young
"Monolithic Circuits for the WA98 Lead Glass Calorimeter"

Frontiers in Education Conference, San Jose, Calif., Nov. 2-6, 1994

Oliver, C. E., M. R. Strayer, and V. M. Umar (Invited Presentation)
"Building an Electronic Book on the Internet: 'CSEP — An Interdisciplinary Syllabus for Teaching Computational Science at the Graduate Level' "

Oliver, C. E., M. R. Strayer, and V. M. Umar (Invited Presentation)
"Teaching Interdisciplinary Computational Science from an Electronic Book on the Internet"

13th International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, Nov. 7-10, 1994

Alton, G. D. (Invited Presentation)
"Ion Sources for Initial Use at the Holifield Radioactive Ion Beam Facility"

Dellwo, J. (Invited Presentation)
"Target Selection for the HRIBF Project"

Havener, C. C. (Invited Presentation)
"Collisions of Highly Charged Ions with Electrons, Atoms, and Surfaces"

Lee, D. H., W. D. Brandon, D. J Pegg, J. Dellwo, and G. D. Alton
"Shape Resonance States Observed in Collisions of Li^- and B^- Ions with Gas Targets"

Levin, J. C. (Invited Presentation)
"Measurements of Single-to-Double Ionization Ratios of Helium Using Synchrotron X Rays"

Ovchinnikov, S. Y., and J. Macek
"Mechanisms of Ionization for Low Energy Ion–Atom Collisions"

Pegg, D. J. (Invited Presentation)
"Photodetachment Cross Sections"

Pieksma, M., S. Y. Ovchinnikov, J. van Eck, W. B. Westerveld, and A. Niehaus
"Low Energy Electrons in Slow Ion–Atom Collisions"

Reinhold, C. O., J. Burgdorfer, K. Kimura, and M. Mannami (Invited Presentation)
"Convoy Electron Emission from Surfaces"

Sanders, J. M. (Invited Presentation)
"Variation of the Binary Encounter Peak Energy as a Function of Projectile Atomic Number"

Shinpaugh, J. L. (Invited Presentation)
"A New Technique for the Study of Charge Transfer in Multiply Charged Ion–Ion Collisions"

Smith, M. S. (Invited Presentation)
"Nuclear Astrophysics at the Holifield Radioactive Ion Beam Facility"

Varner, R. L. (Invited Presentation)
"A BaF_2 Detector Array Used for Nuclear Gamma-Ray Studies"

Wehlitz, R. (Invited Presentation)
"Coincidence Experiments Following Synchrotron Radiation Excitation"

Wells, J. C. (Invited Presentation)
"Lattice Calculation for Lepton Capture from Vacuum Pair Production in Relativistic Heavy-Ion Collisions"

American Physical Society, Division of Plasma Physics, Minneapolis, Minn., Nov. 7-11, 1994

Ma, C. H., D. P. Hutchinson, R. K. Richards, J. Irby, and T. Luke
"A CO_2 Laser Polarimeter for Measurement of Plasma Current Profile Alcator C-Mod"

Richards, R. K., D. P. Hutchinson, C. H. Ma, and Y. Takase
"A CO_2-Laser Thomson Scattering Ion-Tail Diagnostic for Alcator C-Mod"

Specialists' Meeting on Measurement, Calculation, and Evaluation of Photon Production Data, Bologna Italy, Nov. 8-11, 1994

Dickens, J. K., and D. C. Larson
"In-Beam Gamma-Ray Spectrometric Measurements of Multibody Breakup Reactions for E_n Between Threshold and 40 MeV"

American Physical Society, Southeastern Section, Newport News, Vir., Nov. 10-12, 1994

Piercey, R. B., C. J. Beyer, P. G. Varnette, R. A. Belshe, R. Fos, R. W. Macleod, R. L. Varner, and M. Brinkman
"The Common Histogram Object: File Format and Programming Model," Bull. Am. Phys. Soc. 39, 1825 (Nov. 1994)

Supercomputing '94, Washington, D.C., Nov. 14-18, 1994

Chinn, C. R., A. S. Umar, M. R. Strayer, and M. Vallieres
"Static and Dynamic Nuclear Many-Body Descriptions on Parallel Architectures"

Fourth U.S./Mexico Joint Symposium on Atomic and Molecular Physics, San Juan Del Rio, Mexico, Dec. 7-10, 1994

Schultz, D. R. (Invited Presentation)
"The Fully Correlated Two-Electron Problem on a Numerical Lattice"

4th International Workshop on Classical Quantum Correspondence, Philadelphia, Pa., 1994

Burgdorfer, J., and C. Reinhold (Invited Presentation)
"Evolution of Rydberg States in Half-Cycle Pulses: Classical, Semiclassical, and Quantum Dynamics"

1995

XVIII Nuclear Physics Symposium, Oaxtepec, Mexico, Jan. 4-7, 1995

Werner, T. R., J. Dobaczewski, and W. Nazarewicz (Invited Presentation)
"Physics of Drip-Line Nuclei"

Eleventh International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter '95), Monterey, Calif., Jan. 9-13, 1995

Awes, T. C. (Invited Presentation)
"Search for Direct Photon Production in 200 A GeV S + Au Reactions: A Status Report"

Awes, T. C., C. L. Britton, L. G. Clonts, M. S. Emery, M. N. Ericson, F. Plasil, S. Saini, M. L. Simpson, P. W. Stankus, J. W. Walker, A. L. Wintenberg, G. R. Young, B. W. Kolb, S. Neumaier, M. L. Purschke, V. Manko, A. Tsvetkov, A. Vinogradov, N. Heine, T. Peitzmann, and R. Santo
"Monolithic Electronics for the WA98 Lead-Glass Calorimeter"

Chatterjee, L., and C. Y. Wong
"Corrections to Reactions Cross Sections in Quark-Gluon Plasma"

Stankus, P. W.
"Final Results for Single Photons Measured in WA80"

Conference on High-Performance Computing Technologies and Scientific Applications (Mardi Gras '95), Baton Rouge, La., Feb. 23-25, 1995

Chinn, C. R., A. S. Umar, M. R. Strayer, and M. Vallieres
"Microscopic Nuclear Mean Field Calculations on Parallel Architectures"

Workshop on Physics and Detectors for DAPHNE '95, Frascati, Italy, Apr. 4-7, 1995

Barnes, F. E. (Invited Presentation)
"KN Scattering in the Nonrelativistic Quark Model"

Joint Meeting of the American Physical Society and the American Association of Physics Teachers, Washington, D.C., Apr. 18-21, 1995

Awes, T. C. (Invited Presentation)
"Experimental Observations of Electromagnetic Probes of High Density Matter," *Bull. Am. Phys. Soc.* **40**, 988 (Apr. 1995)

Chatterjee, L., and C. Y. Wong
"Corrections to q$\bar{q}$ Reaction Cross Sections in Quark-Gluon Plasma," *Bull. Am. Phys. Soc.* **40**, 923 (Apr. 1995)

Jin, H. Q., C. Baktash, M. J. Brinkman, C. J. Gross, D. G. Sarantites, P.-F. Hua, D. R. LaFosse, B. Cederwall, I. Y. Lee, A. O. Macchiavelli, W. Rathburn, F. Cristancho, E. Landulfo, J. X. Saladin, J. Doring, and S. L. Tabor
"Identification of a Superdeformed Band in ^{84}Zr," *Bull. Am. Phys. Soc.* **40**, 1007 (Apr. 1995)

Kamyshkov, Yu. A., R. A. Lillie, F. Plasil, S. Raman, M. J. Rennich, G. R. Young, W. M. Bugg, H. O. Cohn, G. T. Condo, Yu. V. Efremenko, and K. D. Shmakov

"New Proposal to Search for Neutron-Antineutron Oscillations at Advance Neutron Source Reactor," *Bull. Am. Phys. Soc.* **40**, 1026 (Apr. 1995)

Young, G. R., T. C. Awes, G. T. Alley, C. L. Britton, L. Clonts, M. S. Emery, F. Plasil, S. Saini, M. L. Simpson, P. W. Stankus, J. Walker, and A. L. Wintenberg
"Monolithic Electronics for the WA98 Lead Glass Calorimeter," *Bull. Am. Phys. Soc.* **40**, 921 (Apr. 1995)

European Physics Society XV Nuclear Physics Conference, St. Petersburg, Russia, Apr. 18-22, 1995

Hamilton, J. H., G. M. Ter-Akopian, Yu. Ts. Oganessian, A. V. Daniel, J. Kormicki, G. S.Popeko, A. V. Ramayya, Q.-H. Lu, K. Butler-Moore, W.-C. Ma, S. Cwiok, W. Nazarewicz, W. Greiner, A. Sandulescu, J. K. Deng, D. Shi, J. Kliman, M. Morhac, J. D. Cole, R. Aryaeinejad, S. Zhu, R. Babu, N. R. Johnson, I. Lee, F. K. McGowan, and J. S. Saladin
"A New Spontaneous Fission Mode for ^{252}Cf: Hyperdeformation, Cluster Radioactivity, New Levels"

Twelfth International Workshop on ECR Ion Sources, Wako-shi, Japan, Apr. 25-27, 1995

Alton, G. D., and D. N. Smithe (Invited Presentation)
"A Single-Frequency ECR Ion Source with a Large Uniformly Distributed Resonant Plasma Volume"

1995 Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, Texas, May 1-5, 1995

Alton, G. D., D. Becher, J. Dellwo, G. D. Mills, S. N. Murray, and R. F. Welton
"A Compact RF Multi-Cusp, Filter Field, Positive Ion Source for Radioactive Ion Beam Generation," *Bull. Am. Phys. Soc.* **40**, 1060 (May 1995)

Alton, G. D., J. Dellwo, G. D. Mills, S. N. Murray, and R. F. Welton
"Design Aspects of a Compact Geometry, High-Temperature ECR Ion Source for Radioactive Ion Beam Generation," *Bull. Am. Phys. Soc.* **40**, 1171 (May 1995)

Bailey, J. D.
"ORIC Central Region Calculations," *Bull. Am. Phys. Soc.* **40**, 1102 (May 1995)

Bailey, J. D.
"Axial Injection and Phase Selection Studies of the MSU K1200 Cyclotron," *Bull. Am. Phys. Soc.* **40**, 1102 (May 1995)

Bailey, J. D., J. J. Kuchar, F. Marti, and J. Ottarson
"An Internal Timing Probe for Use in the MSU K1200 Cyclotron," *Bull. Am. Phys. Soc.* **40**, 1102 (May 1995)

Dowling, D. T., R. L. Auble, M. R. Dinehart, D. L. Haynes, J. W. Johnson, R. C. Juras, Y. S. Kwon, M. J. Meigs, G. D. Mills, S. W. Mosko, D. K. Olsen, B. A. Tatum, C. Williams, and H. Wollnik
"Status of the Radioactive Ion Beam Injector at the Holifield Radioactive Ion Beam Facility," *Bull. Am. Phys. Soc.* **40**, 1125 (May 1995)

Meigs, M. J., D. L. Haynes, C. M. Jones, and C. T. LeCroy
"A New Beam Intensity Monitoring System with Wide Dynamic Range for the Holifield Radioactive Ion Beam Facility," *Bull. Am. Phys. Soc.* **40**, 1125 (May 1995)

Mosko, S. W., J. D. Bailey, D. T. Dowling, S. N. Lane, D. K. Olsen, and B. A. Tatum
"Use of ORIC as a High Current Injector for the HRIBF," *Bull. Am. Phys. Soc.* **40**, 1102 (May 1995)

Olsen, D. K. (Invited Presentation)
"First Generation ISOL Radioactive Ion Beam Facilities," *Bull. Am. Phys. Soc.* **40**, 1209 (May 1995)

Tatum, B. A., R. C. Juras, and M. J. Meigs
"Control System for the Holifield Radioactive Ion Beam Facility," *Bull. Am. Phys. Soc.* **40**, 1065 (May 1995)

Third International Conference on Swift Heavy Ions in Matter (SHIM 95), Caen, France, May 15-19, 1995

Vane, C. R., S. Datz, H. F. Krause, E. Deveney, P. Grafstrom, R. Hutton, H. Knudsen, and R. H. Schuch (Invited Presentation)
"Measurements of Electron-Positron Pair Production and Electron Capture in Ultrarelativistic Coulomb Collisions"

American Physical Society, Division of Atomic, Molecular, and Optical Physics, May 16-19, 1995

Bannister, M. R., F. W. Meyer, Y. S. Chung, N. Djuric, G. H. Dunn, M. S. Pindzola, and D. C. Griffin
"Electron-Impact Single Ionization of Mo^{4+} and Mo^{5+}," *Bull. Am. Phys. Soc.* **40**, 1291 (May 1995)

Burgdorfer, J., J. H. McGuire, and J. Wang
"Relationship Between the Ratios of Double to Single Ionization of Helium by Photons and Charged Particles, *Bull. Am. Phys. Soc.* **40**, 1300 (May 1995)

Havener, C. C., M. E. Minear, and M. Pieksma
"Measurements of Electron Capture by Si^{4+} from Deuterium at Near-Thermal Collision Energies," *Bull. Am. Phys. Soc.* **40**, 1322 (May 1995)

Lim, J. Y., H. Lebius, R. Minniti, and S. B. Elston
"Peak Shape Comparison of Convoy Electron Emission from Ion-Atom, Ion-Foil, and Grazing-Incidence Ion-Surface Collisions," *Bull. Am. Phys. Soc.* **40**, 1341 (May 1995)

Mansky, E. J. (Invited Presentation)
"Recent Advances in Electron-Metastable Atom Collision Theory," *Bull. Am. Phys. Soc.* **40**, 1305 (May 1995)

Meyer, F. W. (Invited Presentation)
"The Evolving Role of Atomic Collisions in Fusion Research," *Bull. Am. Phys. Soc.* **40**, 1297 (May 1995)

Minniti, R., H. Lebius, J. Y. Lim, and S. B. Elston
"Convoy Electron Emission in Fast Grazing Ion-Surface Interactions," *Bull. Am. Phys. Soc.* **40**, 1342 (May 1995)

Ovchinnikov, S. Y., and J. H. Macek
"New Theory of Electron Energy and Angular Distribution for Low Energy Ion-Atom Collisions," *Bull. Am. Phys. Soc.* **40**, 1322 (May 1995)

Pieksma, M., and C. C. Havener
"Ionization of H by Slow Fully Stripped Ions," *Bull. Am. Phys. Soc.* **40**, 1323 (May 1995)

Qiu, Y., J. Muller, and J. Burgdorfer
"Periodic Orbit of One- and Two-Electron Atoms," *Bull. Am. Phys. Soc.* **40**, 1301 (May 1995)

Reinhold, C. O., and J. Burgdorfer
"Quantum and Classical Oscillations in Ionization of Stark Rydberg States by Half-Cycle Pulses," *Bull. Am. Phys. Soc.* **40**, 1303 (May 1995)

Wehlitz, R., J. Bozek, B. Langer, A. Farhat, and N. Berrah
"High-Resolution Study of the Ne $2s \rightarrow np$ Autoionization Resonances," *Bull. Am. Phys. Soc.* **40**, 1309 (May 1995)

16th International Symposium on Molecular Beams, Ma'ale Hachamisha, Israel, May 21-26, 1995

Datz, S. (Invited Presentation)
"Dissociative Recombination of H_3^+ and H_2D^+, Rates, Branching Ratios, and Isotope Effects"

Conference on New Perspectives in Nuclear Structure, Ravello, Italy, May 22-26, 1995

Baktash, C. (Invited Presentation)
"Spectroscopy of Far-from-Stability Nuclei"

Physics Computing '95, Annual Meeting of the American Physical Society, Division of Computational Physics, Pittsburgh, Penn., June 5-8, 1995

Oberacker, V. E., A. S. Umar, J. C. Wells, and M. R. Strayer
"Study of Nuclear Matter Viscosity in Muon-Induced Fission," *Bull. Am. Phys. Soc.* **40**, 1358 (June 1995)

International Conference on Exotic Nuclei and Atomic Masses (ENAM 95), Arles, France, June 19-23, 1995

Batchelder, J. C., K. S. Toth, D. M. Moltz, T. J. Ognibene, M. W. Rowe, C. R. Bingham, E. F. Zganjar, and B. E. Zimmerman (Invited Presentation)
"Study of $^{189}Bi^{m}$ α Decay"

Davids, C. N., P. J. Woods, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson, S. J. Freeman, M. Freer, D. J. Henderson, R. J. Irvine, R. D. Page, H. R. Penttila, A. V. Ramayya, D. Seweryniak, K. S. Toth, W. B. Walters, A. H. Wuosmaa, and B. E. Zimmerman (Invited Presentation)
"New Heavy Proton Radioactivities"

Davids, C. N., P. J. Woods, H. T. Penttila, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson, S. J. Freeman, M. Freer, D. J. Henderson, R. J. Irvine, P. K. Joshi, R. D. Page, A. V. Ramayya, K. S. Toth, W B Walters, A. H. Wuosmaa, and B. E. Zimmerman (Invited Presentation)

"Discovery of the Heaviest Known Proton Emitters ^{167}Ir and ^{171}Au Using the Argonne Fragment Mass Analyzer"

Hamilton, J. H., Q. H. Lu, S. J. Zhu, K. Butler-Moore, A. V. Ramayya, W.-C. Ma, B.R.S. Babu, T. N. Ginter, J. Kormicki, J. K. Deng, D. Shi, L. K. Peker, J. O. Rasmussen, M. A. Stoyer, S. Y. Chu, K. E. Gregorich, M. F. Mohar, S. Prussin, J. D. Cole, R. Aryaeinejad, N. R. Johnson, I. Y. Lee, F. K. McGowan, G. M. Ter-Akopian, and Yu. Ts. Oganessian
"Extended Identical Bands in ^{98,100}Sr and ^{108,110}Ru and New High Spin States in ^{98,102}Zr and $^{112-116}$Pd"

Penttila, H., C. N. Davids, P. J. Woods, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, S. J. Freeman, M. Freer, D. J. Henderson, R. D. Page, A. V. Ramayya, K. S. Toth, W. B. Walters, A. H. Wuosmaa, and B. E. Zimmerman (Invited Presentation)
"Proton Radioactivity Studies at the FMA"

Toth, K. S., J. C. Batchelder, L. F. Conticchio, W. B. Walters, C. R. Bingham, J. D. Richards, B. E. Zimmerman, C. N. Davids, H. Penttila, D. J. Henderson, R. Hermann, and A. H. Wuosmaa (Invited Presentation)
"The α-Decay Properties of ^{181}Pb"

Werner, T. R., J. Dobaczewski, and W. Nazarewicz
"Closed Shells at Drip Lines"

Zhu, S. J., J. H. Hamilton, A. V. Ramayya, Q. Lu, W.-C. Ma, B.R.S. Babu, J. Kormicki, T. N. Ginter, J. K. Deng, L. K. Peker, J. O. Rasmussen, M. A. Stoyer, S. Y. Chu, K. E. Gregorich, M. F. Mohar, S. Prussin, J. D. Cole, R. Aryaeinejad, N. R. Johnson, I. Y. Lee, F. K. McGowan, G. M. Ter-Akopian, and Yu. Ts. Oganessian
"Identification of Levels in ^{152}Ce, ^{160}Sm, and Higher Spin States and Identical Bands in Neutron-Rich Ce, Nd, Sm Isotopes"

Zhu, S. J., M. G. Wang, Q. Lu, J. H. Hamilton, A. V. Ramayya, W.-C. Ma, J. Kormicki, B.R.S. Babu, T. Ginter, D. Shi, J. K. Deng, L. K. Peker, J. O. Rasmussen, M. A. Stoyer, S. Y. Chu, K. E. Gregorich, M. F. Mohar, S. Prussin, J. D. Cole, R. Aryaeinejad, N. R. Johnson, I. Y. Lee, F. K. McGowan, G. M. Ter-Akopian, and Yu. Ts. Oganessian
"Octupole Deformation in Neutron-Rich ^{142,143}Ba and ^{144}Ce Nuclei and Identical Ground and Octupole Bands in ^{144,146}Ba"

Workshop on the Tau/Charm Factory, Argonne, Ill., June 21-23, 1995

Barnes, T. (Invited Presentation)
"Theoretical Predictions for Exotic Hadrons"

American Nuclear Society Meeting, Philadelphia, Penn., June 25-29, 1995

Saleh, H. H., T. A. Parish, and S. Raman
"Measurements of Delayed Neutron Emission from Np-237, Am-241, and Am-243"

TASCC Workshop 95 on Nuclear Physics, Chalk River, Ontario, Canada, June 26-28, 1995

Shapira, D.
"Lifetime and Source Sizes from HI p-p Correlation Studies"

NATO Advanced Study Institute on Hadron Spectroscopy and the Confinement Problem, June 27-July 8, 1995, Swansea, Wales

Barnes, T. (Invited Presentation)
"Theoretical Aspects of Light Meson Spectroscopy"

Conference on Giant Resonances, Gronigen, Netherlands, June 28-July 1, 1995

Beene, J. R. (Invited Presentation)
"Probing Nuclear Structure and Dynamics with Giant Resonance Excitation and Decay"

Ormand, W. E., P. F. Bortignon, and R. A. Broglia
"The Temperature Dependence of the Width of the Giant Dipole Resonance"

International Workshop on Relativistic Channeling, Aarhus, Denmark, July 8-15, 1995

Datz, S., C. R. Vane, H. F. Krause, E. F. Deveney, H. Knudsen, P. Grafstrom, R. H. Schuch, and R. Hutton (Invited Presentation)
"Complete Energy Loss of 33-TeV Pb Ions in Carbon"

6th International Conference on Hadron Spectroscopy, Manchester, England, July 10-14, 1995

Barnes, T. (Invited Presentation)
"The Mechanism of Open-Flavor Strong Decays"

16th International Conference on Atomic Collisions in Solids, Linz, Austria, July 17-20, 1995

Datz, S. (Invited Presentation)
"Crystal Assisted Processes in Ion Channeling"

Reinhold, C. O., J. Burgdorfer, K. Kimura, and M. Mannami
"Electron Transport of Fast Electrons Near Surfaces"

XIX International Conference on the Physics of Electronic and Atomic Collisions, Whistler, B.C., Canada, July 26-Aug. 1, 1995

Burgdorfer, J., C. Reinhold, and F. Meyer (Invited Presentation)
"Fast Neutralization of Highly Charged Ions in Grazing Incidence Collisions with Surfaces"

Burgdorfer, J., C. Reinhold, J. Sternberg, and J. Wang (Invited Presentation)
"Semiclassical Theory of Elastic Electron-Atom Scattering"

Datz, S., M. Larsson, C. Stromholm, G. Sundstrom, V. Zengin, H. Danared. A. Kallberg, and M. af Ugglass
"Dissociative Recombination of H_2D^+ Studied in the Cryring Heavy Ion Storage Ring"

Deveney, E. F., H. F. Krause, N. L. Jones, J. M. Sanders, C. R. Vane, W. Wu, S. Datz, M. Breinig, D. Desai, S. Y. Ovchinnikov, Q. C. Kessel, and S. M. Shafroth (Invited Presentation)
"Nonstatistically Populated Autoionizing Levels of Li-Like Carbon: Hidden Crossings"

Elston, S. B., H. Lebius, J. Y. Lim, and R. Minniti (Invited Presentation)
"Convoy Electrons Produced in Grazing-Incidence Ion-Surface Collisions"

Folkerts, L., S. Schippers, H. O. Folkerts, Q. Yan, J. Burgdorfer, and F. W. Meyer (Invited Presentation)
"Scattered Ion Angular and Charge State Distributions Resulting from Low Energy Grazing Interactions of Multicharged Ions with Au(110)

Hsu, Y. Y., G. W. Kerby III, M. W. Gealy, M. E. Rudd, C. O. Reinhold, and D. R. Schultz
"Energy and Angular Distributions of Electrons Ejected in Collisions of H^+ with He^+ with H and H_2"

Kojima, T. M., M. E. Bannister, and X. Guo
"Electron-Impact Dissociation of DCO^+ into CO^+ Fragment"

Krause, H. F., C. R. Vane, S. Datz, E. Deveney, P. Grafstrom, R. Hutton, H. Knudsen, and R. H. Schuch
"Electron Capture from Pair Production in Collisions of 160-GeV/U Lead"

Krstic, P.
"Extension of the Hidden-Crossing Method to Multi-Electron, Multi-Center Systems"

Lee, D. H., W. D. Brandon, and D. J. Pegg
"Structure in Zero-Degree Detachment Electron Spectra for 100 keV B^- + He (Ar) Collisions"

Passovets, S. V., J. H. Macek,and S. Ovchinnikov (Invited Presentation)
"Basis Spline Method for e^- + H Collisions"

Pieksma, M., and C. C. Havener
"Ionization of H by Adiabatic Multicharged Ion Impact"

Reinhold, C. and J. Burgdorfer (Invited Presentation)
"Dynamics of Extreme Stark States in Half-Cycle Pulses"

Reinhold, C., J. Burgdorfer, K. Kimura, and M. Mannami (Invited Presentation)
"Convoy Electron Emission from Surfaces"

Sanders, J. M., M. Breinig, S. Datz, E. F. Deveney, N. L. Jones, J. L. Shinpaugh, C. R. Vane, D. Desai, and F. Segner (Invited Presentation)
"Binary Encounter Electron Production at Atom and Ion Projectiles"

Sanders, J. M., S. Datz, R. D. DuBois, and S. T. Manson
"Coincidence Studies of Target and Projectile Ionization in Fast Dressed Particle Collisions"

Schultz, D. R. (Invited Presentation)
"Time-Dependent Lattice Approach to Atomic Collisions"

Vane, C. R., H. F. Krause, S. Datz, E. Deveney, P. Grafstrom, R. Hutton, H. Knudsen, and R. H. Schuch
"Measurements of Positrons Formed by Coulomb Excitation of the Negative Continuum in Collisions of 33-TeV Lead Ions"

Wu, W., C. L. Cocke, S. Datz, J. P. Giese, and C. R. Vane
"Target Direct Ionization by Slow, Highly Charged Ions: A Scaling Rule"

3rd Workshop on Nuclear Spectroscopy by Use of JAERI Tandem Booster, Tokai, Japan, July 27-28, 1995

Zhang, J.-Y., Y. Sun, and M. W. Guidry
"$\Delta I = 4$ Bifurcation: Origins and Criteria"

International Nuclear Physics Conference (INPC '95), Beijing, China, Aug. 21-26, 1995

Garrett, J. D. (Invited Presentation)
"Nuclear Structure and Astrophysics with Accelerated Beams of Radioactive Ions: A New Multidisciplinary Research Tool"

Plasil, F.
"Photon Emission in Collisions Between 200-GeV/Nucleon ^{32}S Ions and ^{197}Au Nuclei"

Wong, C. Y. (Invited Presentation)
"Suppression of ψ' and J/ψ in High-Energy Heavy-Ion Collisions"

Young, G. R. (Invited Presentation)
"Physics and Experiments at RHIC"

XXIV Mazurian Lakes School of Physics, Piaski, Poland, Aug. 23-Sept. 2, 1995

Korolija, M., D. Shapira, and N. Cindro (Invited Presentation)
"Proton-Proton Intensity Interferometry: Space–Time Structure of the Emitting Zone in Ni + Ni Collisions"

Nazarewicz, W. (Invited Presentation)
"Perspectives in High Spin Physics (Theoretical Remarks)"

Workshop on Diagnostics for ITER, Varenna, Italy, Aug. 28-Sept. 1, 1995

Hutchinson, D. P., R. K. Richards, and C. H. Ma
"Infrared Laser Diagnostics for ITER"

Snider, R. T., T. N. Carlstrom, C. H. Ma, and W. A. Peebles
"Application of Interferometry and Faraday Rotation Techniques for Density Measurements on ITER"

Radioactive Beam Ion Sources (RBIS) Workshop, Vancouver, Canada, Sept. 6-15, 1995

Alton, G. D., and J. Breitenbach
"Characteristics of HRIBF Electron Beam Plasma Sources"

Alton D. G., G. di Bartolo, W. L. Talbert, J. W. Middleton, and C. Williams
"The Ionization and Molecular Dissociation Properties of a Filter Field, RF Positive Ion Source"

Alton, G. D., and G. D. Mills (Invited Presentation)
"A New Concept, Positive/Negative Surface Ionization Source"

Alton, G. D., and C. Williams
"A New Concept, Combined Thermal Dissociator/Electron Impact Ionization Source"

Alton, G. D., and C. Williams
"Provisions for Limiting the Effects of Radiation in Designs for the HRIBF Target/Ion Source Vacuum Housing Assembly"

Di Bartolo, G., G. D. Alton, W. L. Talbert, and J. W. Middleton
"Design Studies for HRIBF Composite Target/Heat Sink-Systems

Welton, R. F., G. D. Alton, A. Pitrowski, and S. N. Murray
"Performance Enhancement of a Compact Radio Frequency Ion Source by the Injection of Supplemental Electrons"

Heavy Ion Accelerator Conference, Canberra, Australia, Sept. 9-13, 1995

Meigs, M. J., D. L. Haynes, C. M. Jones, and R. C. Juras
"Development of the HRIBF 25-MV Tandem Accelerator as a RIB Accelerator

Sixth International Conference on Ion Sources, Whistler, B.C., Canada, Sept. 10-16, 1995

Alton, G. D. (Invited Presentation)
"Selection of Targets and Ion Sources for RIB Generation at the Holifield RIB Facility"

Alton, G. D., G. D. Mills, and J. Breitenbach
"An Improved CERN–ISOLDE-Type Source for RIB Generation"

Alton, G. D., A. Pitrowski, and G. D. Mills
"A High Efficiency Positive/Negative Surface Ionization Source for RIB Generation"

Alton, G. D., A. Pitrowski, G. D. Mills, and S. N. Murray
"A Combined Thermal Dissociation and Electron Impact Ionization-Type Ion Source for RIB Generation"

Alton, G. D., and D. N. Smithe
"Computational Studies for a Multiple-Frequency ECR Ion Source"

Alton, G. D., R. F. Welton, A. Pitrowski, and S. N. Murray
"Performance Characteristics of a Multi-Purpose, Compact, Filter-Field rf Ion Source"

Welton, R. F., G. D. Alton, G. D. Mills, and S. N. Murray
"Performance Enhancement of a Compact Radio Frequency Ion Source by the Injection of Supplemental Electrons"

Welton, R. F., A. Piotrowski, G. D. Alton, and S. N. Murray
"Effusive Flow Delay Times for Gaseous Species in a Compact rf Ion Source"

***Global 95* — International Conference on Evaluation of Emerging Nuclear Fuel Cycle Systems, Versailles, France, Sept. 11-14, 1995**

Raman, S. And B. D. Murphy (Invited Presentation)
"US/UK Actinides Experiment at the Dounreay PFR"

Eurosim '95 Conference, Vienna, Austria, Sept. 11-15, 1995

Goneid, A., M.G.H. Mostafa, and C. Y. Wong
"Simulation of Multiparticle Production in High-Energy Nuclear Interactions"

International Conference on Nucleon-Antinucleon Interactions (NAN '95), Moscow, Russia, Sept. 11-16, 1995

Kamyshkov, Yu. A., W. M. Bugg, H. O. Cohn, G. T. Condo, Yu. V. Efremenko, S. K. Lamoreaux, R. A. Lillie, F. Plasil, S. Raman, M. J. Rennich, K. D. Shmakov, R. Wilson, and G. R. Young
"Future Prospects for Neutron-Antineutron Transition Searches"

Heavy Ion Accelerator Conference, Canberra, Australia, Sept. 13-22, 1995

Meigs, M. J., D. L. Haynes, C. M. Jones, and R. C. Juras (Invited Presentation)
"Development of the HRIBF 25-MV Tandem Accelerator as a RIB Accelerator"

Olsen, D. K., R. L. Auble, G. D. Alton, J. D. Bailey, M. R. Dinehart, C. L. Dukes, D. T. Dowling, D. L. Haynes, C. M. Jones, S. N. Lane, C. T. LeCroy, R. C. Juras, M. J. Meigs, G. D. Mills, S. W. Mosko, P. E. Mueller, S. N. Murray, B. A. Tatum, and R. F. Welton (Invited Presentation)
"First Results from the Holifield Radioactive Ion Beam Facility"

4th International Workshop on Theoretical and Phenomenological Aspects of Underground Physics, Toledo, Spain, Sept. 17-21, 1995

Kamyshkov, Yu. A., W. M. Bugg, H. O. Cohn, G. T. Condo, Yu. V. Efremenko, S. K. Lamoreaux, R. A. Lillie, F. Plasil, S. Raman, M. J. Rennich, K. D. Shmakov, R. Wilson, and G. Young
"Prospects for Neutron-Antineutron Transition Searches"

Seventh International Conference on Heavy-Ion Accelerator Technology, Canberra, Australia, Sept. 17-22, 1995

Alton, G. D. (Invited Presentation)
"Broadband Frequency ECR Ion Source Concepts with Large Resonant Plasma Volumes"

Alton, G. D. (Invited Presentation)
"Targets and Ion Sources for RIB Generation at the Holifield Radioactive Ion Beam Facility"

Alton, G. D., and J. Dellwo
"Selection of RIB Targets Using Ion Implantation at the Holifield Radioactive Ion Beam Facility"

Alton, G. D., G. D. Mills, S. N. Murray, and J. Breitenbach
"An Improved CERN–ISOLDE-Type Source for RIB Generation"

Alton, G. D., G. D. Mills, and C. A. Reed
"The Performance Characteristics of Single and Multiple Sample Cesium-Sputter Negative Ion Sources"

Alton, G. D., G. D. Mills, R. F. Welton, a nd C. A. Reed
"A Compact, High-Intensity, RF/Filament, Plasma-Sputter Heavy Negative Ion Source"

Alton, G. D., A. Pitrowski, and G. D. Mills
"A Positive/Negative Surface Ionization Source for RIB Generation"

Alton, G. D., A. Pitrowski, G. D. Mills, and S. N. Murray
"A Tandem Thermal Dissociation and Electron Impact Ionization Ion Source for RIB Generation"

Alton, G. D., and D. N. Smithe
"A Multiple-Frequency ECR Ion Source: Computational Studies"

Alton, G. D., R. F. Welton, A. Pitrowski, and S. N. Murray
"Characterization of a Multipurpose, Compact, Filter-Field RF Ion Source"

Japan Physical Society Meeting, Kasugai City, Japan, Sept. 27-30, 1995

Raman, S. (Invited Presentation)
"Quadrupole Deformation of Even-Even Nuclei"

7th International Conference on the Structure of Baryons, Santa Fe, New Mexico, Oct. 3-7, 1995

Barnes, T. (Invited Presentation)
"Production and Decay of 'Strange States' "

14th International Conference on Cyclotrons and Their Applications, Cape Town, South Africa, Oct. 8-13, 1995

Alton, G. D. (Invited Presentation)
"Recent Advancements and Future Prospects for ECR Ion Sources with Improved Charge State Distributions"

Olsen, D. K., R. L. Auble, G. D. Alton, J. D. Bailey, M. R. Dinehart, C. L. Dukes, D. T. Dowling, D. L. Haynes, C. M. Jones, S. N. Lane, C. T. LeCroy, R. C. Juras, M. J. Meigs, G. D. Mills, S. W. Mosko, P. E. Mueller, S. N. Murray, and B. A. Tatum
"Status Report on the Holifield Radioactive Ion Beam Facility"

13th Meeting of the International Collaboration on Advanced Neutron Sources, Villigen, Switzerland, Oct. 11-14, 1995

Kamyshkov, Yu. A., W. Bugg, H. Cohn, G. Condo, Yu. Efremenko, S. Lamoreaux, R. Lillie, F. Plasil, S. Raman, M. Rennich, K. Shmakov, R. Wilson, and G. Young
"Use of Cold Source and Large Reflector Mirror Guide for Neutron-Antineutron Oscillation Search (Proposal)"

Symposium of Northeastern Accelerator Personnel (SNEAP-95), Durham, N.C., Oct. 11-15 1995

Jones, N. L.
"Continuing Search for a New Type Charging Belt"

Jones, N. L.
"EN Tandem at ORNL"

Meigs, M. J., D. L. Haynes, and R. C. Juras
"Oak Ridge 25URC Tandem Accelerator"

1995 Nuclear Science Symposium and Medical Imaging Conference, San Francisco, Calif., Oct. 21-28, 1995

Britton, C. L., Jr., A. L. Wintenberg, G. R. Young, T. C. Awes, M. Womac, E. J. Kennedy, and R. S. Smith
"Post-Radiation Memory Correction Using Differential Subtraction for PHENIX"

Ericson, M. N., M. S. Musrock, C. L. Britton, Jr., J. W. Walker, A. L. Wintenberg, and G. R. Young
"A Flexible Analog Memory Address List Manager for PHENIX"

Simpson, M. L., G. R. Young, R. G. Jackson, and M. Xu
"A Monolithic, Constant-Fraction Discriminator Using Distributed R-C Delay-Line Shaping"

American Physical Society, Division of Nuclear Physics, Bloomington, Ind., Oct. 25-28, 1995

Babu, B.R.S., S. J. Zhu, J. H. Hamilton, A. V. Ramayya, W. C. Ma, Q. H. Lu, T. N. Ginter, J. K. Deng, D. Shi, M. G. Wang, J. D. Cole, R. Aryaeinejad, J. O. Rasmussen, M. Stoyer, S. Y. Chu, K. E. Gregorich, M. F. Mohar, S. Prussin, G. M. Ter-Akopian, Yu. Ts. Oganessian, N. R. Johnson, I. Y. Lee, and F. K. McGowan
"Identification of ^{151,153}Nd: High Spin States in $^{148\text{-}156}$Nd," *Bull. Am. Phys. Soc.* **40**, 1616 (Oct. 1995)

Batchelder, J. C., E. F. Zganjar, K. S. Toth, D. M. Moltz, T. J. Ognibene, M. W. Rose, C. R. Bingham, and B. E. Zimmerman
"Excitation Energy of the $\pi s_{1/2}$ Intruder State in ^{189}Bi," *Bull. Am. Phys. Soc.* **40**, 1631 (Oct. 1995)

Blackmon, J. C., A. E. Champagne, J. K. Dickens, M. A. Hofstee, C. Larson, D. C. Ralston, S. Raman, and M. S. Smith
"Measurement of the ^{7}Li(n,γ)^{8}Li Cross Section at E_n = 1–1000 eV," *Bull. Am. Phys. Soc.* **40**, 1612 (Oct. 1995)

Davids, C. N., B. B. Back, D. J. Blumenthal, D. J. Henderson, C. L. Jiang, H. T. Penttila, D. J. Seweryniak, A. H. Wuosmaa, P. J. Woods, T. Davinson, R. J. Irvine, R. D. Page, J. C. Batchelder, P. Joshi, C. R. Bingham, J. D. Richards, B. E. Zimmerman, L. T. Brown, A. V. Ramayya, B. C. Busse, L. F. Conticchio, W. B. Walters, S. J. Freeman, M. Freer, and K. S. Toth
"New Heavy Proton Radioactivities ^{165,166,167}Ir, ^{171}Au, and ^{185}Bi," *Bull. Am. Phys. Soc.* **40**, 1630 (Oct. 1995)

Guber, K. H., R. R. Spencer, R. R. Winters, P. E. Koehler, D. C. Larson, S. Raman, and M. S. Smith
"^{142,144}Nd(n,γ) Cross Sections for Astrophysical s-Process Studies," *Bull. Am. Phys. Soc.* **40**, 1627 (Oct. 1995)

Koehler, P. E., J. A. Harvey, N. W. Hill, R. R. Winters, R. R. Spencer, K. H. Guber, D. C. Larson, S. Raman, and M. S. Smith
"^{134,136}Ba Neutron Total Cross Section Measurements for *s*-Process Studies," *Bull. Am. Phys. Soc.* **40**, 1627 (Oct. 1995)

Oberacker, V. E., A. S. Umar, J. C. Wells, and M. R. Strayer
"Muon-Induced Fission: A Probe for Nuclear Matter Viscosity in Large-Amplitude Collective Motion," *Bull. Am. Phys. Soc.* **40**, 16105 (Oct. 1995)

Ormand, W. E., and B. A. Brown
"Isospin-Mixing Corrections for *fp*-Shell Fermi Transitions," *Bull. Am. Phys. Soc.* **40**, 1606 (Oct. 1995)

Spencer, R. R., R. R. Winters, K. H. Guber, P. E. Koehler, D. C. Larson, S. Raman, and M. Smith
"^{134,136}Ba(n,γ) Cross Sections for *s*-Process Studies," *Bull. Am. Phys. Soc.* **40**, 1627 (Oct. 1995)

Winters, R. R., K. H. Guber, R. R. Spencer, P. E. Koehler, D. C. Larson, S. Raman, and M. S. Smith
"A BaF_2 Detector System for (n,γ) Cross Section Measurements for Astrophysical *s*-Process Studies," *Bull. Am. Phys. Soc.* **40**, 1627 (Oct. 1995)

Yu, C. H.
"Systematic Analyses of Odd-Odd Nuclei in Mass 160 Region," *Bull. Am. Phys. Soc.* **40**, 1624 (Oct. 1995)

Zhu, S. J., J. H. Hamilton, A. V. Ramayya, B.R.S. Babu, W. C. Ma, Q. H. Lu, T. N. Ginter, J. K. Deng, D. Shi, M. G. Wang, J. D. Cole, R. Aryaeinejad, J. O. Rasmussen, M. Stoyer, S. Y. Chu, K. E. Gregorich, M. F. Mohar, S. Prussin, G. M. Ter-Akopian, Yu. Ts. Oganessian, N. R. Johnson, I. Y. Lee, and F. K. McGowan
"High Spin States in ^{112,114,116}Pd," *Bull. Am. Phys. Soc.* **40**, 1615 (Oct. 1995)

37th Annual Meeting, American Physical Society Division of Plasma Physics, Louisville, Kentucky, Nov. 6-10, 1995

Ma, C. H., D. P. Hutchinson, R. K. Richards, and J. Irby
"A Feasibility Study of an Infrared Tangential Viewing Polarimeter for Measurement of the Electron Density Profile in ITER"

Richards, R. K., D. P. Hutchinson, C. H. Ma, and Y. Takase
"A CO_2-Laser Thomson Scattering Diagnostic for Ion-Tail Measurements"

American Physical Society, Meeting of the Southeastern Section, Tallahassee, Fla., Nov. 9-11, 1995

Garrett, J. D. (Invited Presentation)
"The Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory," *Bull. Am. Phys. Soc.* **40**, 2055 (Nov. 1995)

Mezzacappa, A. (Invited Presentation)
"The Mechanism for Core Collapse Supernovae," *Bull. Am. Phys. Soc.* **40**, 2066 (Nov. 1995)

Seventh International Toki Conference on Plasma Physics and Controlled Nuclear Fusion (ITC-7), *Fusion Plasma Diagnostics*, Toki-City Japan, Nov. 28-Dec. 1, 1995

Ma, C. H., D. P. Hutchinson, R. K. Richards, and J. Irby
"An Infrared Polarimeter for Measurement of Plasma Current Profile in Alcator C-Mod"

Richards, R. K., D. P. Hutchinson, and C. H. Ma
"A CO_2 Laser Hot-Ion Thomson Scattering Diagnostic"

Workshop on Gammasphere Physics, Berkeley, Calif., Nov. 30-Dec. 2, 1995

Nazarewicz, W. (Invited Presentation)
"Gammasphere Physics Far from Stability"

International Chemical Congress of Pacific Basin Societies, Honolulu, Hawaii, Dec. 17-22, 1995

Garrett, J. D. (Invited Presentation)
"Initial Scientific Program for the Holifield Radioactive Ion Beam Facility"

1996

XVIII Symposium on Nuclear Physics, Oaxtepec, Mexico, Jan. 3-6, 1996

Gomez del Campo, J., D. Shapira, E. Chavez, M. E. Ortiz, A. Dacal, A. D'Onofrio, and F. Terrasi (Invited Presentation)
"Coincidences Between Light Particles, Evaporation Residues, and Complex Fragments in the Reaction ^{58}Ni + ^{58}Ni at 500 MeV Bombarding Energy"

16th Werner Brandt Workshop on Charged Particle Penetration Phenomenon, Oak Ridge, Tenn., Jan. 8-9, 1996

Datz, S., C. R. Vane, H. F. Krause, and E. F. Deveney
"Stopping of Ultrarelativistic Ions in Solids (33.2-TeV ^{108}Pb)"

Yan, Q., and F. Meyer
"Scattered Projectile Angular and Charge State Distributions for Grazing Collisions of Multicharged Ions with Metal and Insulator Single Crystal Targets"

Tenth American Physical Society Topical Conference on Atomic Processes in Plasmas, San Francisco, Calif., Jan. 14-18, 1996

Havener, C. C. (Invited Presentation)
"Measurements of Charge-Exchange Cross Sections for Collisions of Multicharged Ions with Atomic Hydrogen from keV to Thermal Collision Energies"

Schultz, D. R., and J. K. Nash
"On-Line Atomic Data Access"

Twelfth Winter Workshop on Nuclear Dynamics, Snowbird, Utah, Feb. 3-10, 1996

Plasil, F. (Invited Presentation)
"Measurement of Direct Photons in 200 · A GeV ^{32}S + Au Collisions"

International Workshop on Future Prospects of Baryon Instability Search in p-Decay and $n \rightarrow \bar{n}$ Oscillation Experiments, Oak Ridge, Tenn., Mar. 28-30, 1996

Efremenko, Yu., W. Bugg, H. Cohn, Yu. Kamyshkov, G. Parker, and F. Plasil
"Prospects for Baryon Instability Search in Neutron-Antineutron Oscillations"

Kamyshkov, Yu. (Invited Presentation)
"Prospects for Neutron-Antineutron Transition Search"

German Physical Society, Spring Meeting, Stuttgart Germany, Mar. 25-29, 1996

Baktash, C., M. J. Brinkman, C. J. Gross, H.-Q. Jin, D. Rudolph, C. H. Yu, M. Devlin, D. R. LaFosse, D. G. Sarantites, G. Sylvan, S. L. Tabor, I. Birriel, J. X. Saladin, V. Wood, I. Y. Lee, and A. O. Macchiavelli
"Systematics of Superdeformed Bands in the A ≈ 80 Nuclei"

Rudolph, D., C. Baktash, C. J. Gross, H.-Q. Jin, C. H. Yu, M. Devlin, D. R. LaFosse, D. G. Sarantites, J. Doring, G. Sylvan, S. L. Tabor, I. Birriel, J. X. Saladin, V. Wood, I. Y. Lee, and A. O. Macchiavelli
"Band Crossing Phenomena in the T = 1 Nuclei ^{78}Sr, ^{82}Zr, and ^{86}Mo"

Contemporary Shell Model Workshop, Philadelphia, Penn., Apr. 29-30, 1996

Koonin, S. E., and D. J. Dean (Invited Presentation)
"Shell-Model Monte Carlo Methods"

1996 Joint Meeting of the American Physical Society and American Association of Physics Teachers, Indianapolis, Ind., May 2-5, 1996

Batchelder, J. C., E. F. Zganjar, K. S. Toth, D. M. Moltz, T. J. Ognibene, J. Powell, M. W. Rowe, and C. R. Bingham
"Determination of the ^{190}Po α Reduced Width"

Bingham, C. R., B. E. Zimmerman, K. S. Toth, J. C. Batchelder, D. J. Blumenthal, C. N. Davids, D. Seweryniak, L. T. Brown, B. C. Busse, L. F. Conticchio, W. B. Walters, T. Davinson, R. J. Irvine, and P. J. Woods
"Investigation of Nuclides near the Proton Drip Line via α Decay"

Garrett, J. D.
"Neutron-Proton Correlations in Self-Conjugate Nuclei"

Olsen, D. K. (Invited Presentation)
"The Oak Ridge HRIBF and Beyond"

Shapira, D., J. Gomez del Campo, M. Korolija, and E. Chavez
"Study of Collisions Induced by 11 MeV/Nucleon ^{58}Ni + ^{24}Mg"

Yu, C.-H., C. Baktash, M. J. Brinkman, C. J. Gross, H.-Q. Jin, D. Rudolph, M. Devlin, D. R. Fosse, F. Lerma, D. G. Sarantites, G. Sylvan, S. Tabor, R. M. Clark, P. Fallon, I. Y. Lee, A. O. Machiavelli, I. Birriel, J. X. Saladin, D. Winchell, and V. Wood
"Lifetime Measurement of Superdeformed Band in ^{82}Sr"

1996 Scanning Microscopy Meeting, Washington, D.C., May 11-16, 1996

Meyer, F. W., and Q. Yan
"Neutralization of Multicharged Ions Interacting with Metals and Insulators"

1996 International Symposium on Circuits and Systems, Atlanta, Ga., May 12-15, 1996

Britton, C. L., Jr., W. L. Bryan, M. S. Emery, M. N. Ericson, M. S. Musrock, M. L. Simpson, J. W. Walker, A. L. Wintenberg, F. Plasil, G. R. Young, M. D. Allen, L.G. Clonts, E. J. Kennedy, R. S. Smith, J. Boissevain, B. V. Jacak, J. Kapustinsky, J. Simon-Gillo, J. P. Sullivan, H. Van Hecke, and N. Xu
"Low Noise, Low Power Dissipation Analog LSI Electronics for Heavy Ion Detectors"

Workshop on Strangeness in Hadronic Matter, Budapest, Hungary, May 15-17, 1996

Wong, C. Y., and L. Chatterjee
"Effects of Final-State Interaction and Screening on $s\bar{s}$ Production Cross Sections"

American Physical Society, Division of Atomic, Molecular, and Optical Physics, Ann Arbor, Mich., May 15-18, 1996

Datz, S., H. F. Krause, C. R. Vane, E. F. Deveney, H. Knudsen, R. Schuch, and P. Grafstrom
"Energy Loss of 33.2-TeV Pb Ions in Solids," *Bull. Am. Phys. Soc.* **41**, 1129 (May 1996)

Krause, H. F., C. R. Vane, E. F. Deveney, S. Datz, H. Knudsen, and R. Schuch
"Unique Apparatus for Performing Remotely Controlled Experiments at CERN," *Bull. Am. Phys. Soc.* **41**, 1098 (May 1996)

Schultz, D. R., P. S. Krstic, C. O. Reinhold, and J. C. Wells
"Ionization of Hydrogen and Hydrogenic Ions by Antiprotons," *Bull. Am. Phys. Soc.* **41**, 1089 (May 1996)

Vane, C. R. (Invited Presentation)
"Atomic Collisions with 33-TeV Lead Ions," *Bull. Am. Phys. Soc.* **41**, 1106 (May 1996)

Wells, J. C., D. R. Schultz, P. Gavras, and M. S. Pindzola
"3D Lattice Calculations for Ionization in Intermediate Energy Antiproton-Hydrogen Collisions," *Bull. Am. Phys. Soc.* **41**, 1137 (May 1996)

Wu, W., S. Datz, N. L. Jones, H. F. Krause, C. R. Vane, and B. Rosner
"Double Ionization of He by Proton Impact at Large Energy Transfer," *Bull. Am. Phys. Soc.* **41**, 1056 (May 1996)

Twelfth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Heidelberg, Germany, May 20-24, 1996

Wong, C. Y. (Invited Presentation)
"Suppression of ψ' and J/ψ in High-Energy Heavy-Ion Collisions"

Fourth International Conference on Radioactive Nuclear Beams, Omiya, Japan, June 4-7, 1996

Baktash, C.
"Nuclear Structure Studies Near Proton Drip Line at ORNL: Plans, Techniques, and Detectors"

Garrett, J. D. (Invited Presentation)"
"The Latest from the New Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory

Smith, M. S.
"Nuclear Astrophysics at the Holifield Radioactive Ion Beam Facility"

International Conference on Modelling and Simulation in Metallurgical Engineering and Materials Science, Beijing, China, June 11-13, 1996

Alton, G. D., and J. W. Middleton (Invited Presentation)
"Targets and Ion Sources for RIB Generation at the Holifield Radioactive Ion Beam Facility"

Nuclei in the Cosmos IV, Notre Dame, Ind., June 20-29, 1996

Guber, K. H., R. R. Spencer, R. R. Winters, and P. E. Koehler
"A BaF_2 Detector System for (n,γ) Cross Section Measurements at ORELA for *s*-Process at Low Temperatures Studies"

Guber, K. H., R. R. Spencer, R. R. Winters, and P. E. Koehler
"Measurements of $^{142,144}Nd$ (n,γ) Cross Sections at ORELA for Astrophysical *s*-Process Studies"

Koehler, P. E., R. R. Spencer, R. R. Winters, K. H. Guber, J. A. Harvey, and N. W. Hill
"New (n,γ) and Total Cross Section Measurements for ^{134,136}Ba and Their Impact on *s*-Process Nucleosynthesis Calculations"

1996 EPF/DPB Summer Study on New Directions for High-Energy Physics (Snowmass 96), Snowmass, CO, June 25-July 12, 1996

Efremenko, Yu., and Yu. Kamyshkov
"Prospects of a Baryon Instatility Search in Neutron-Antineutron Oscillations"

International Conference on Nuclear Structure Around the Turn of the Century, Crete, Greece, July 1-6, 1996

Batchelder, J. C., K. S. Toth, D. M. Moltz, E. F. Zganjar, T. J. Ognibene, M. W. Rowe, C. R. Bingham, J. Powell, and B. E. Zimmerman
"Alpha Decay Studies of ^{189}Bi^{m}, ^{190}Po, and ^{180}Pb Using a Rapidly Rotating Recoil Catcher Wheel System"

Gross, C. J.
"HRIBF: Status and Plans for the Near Future"

Rudolph, D., C. Baktash, M. J. Brinkman, C. J. Gross, H.-Q. Jin, W. Satula, C. H. Yu, M. Devlin, D. R. LaFosse, D. G. Sarantites, G. Sylvan, S. L. Tabor, I. Birriel, J. X. Saladin, V. Wood, I. Y. Lee, and A. O. Macchiavelli (Invited Presentation)
"Results from GAMMASPHERE in the A $\approx$ 80 Region: Superdeformed Bands and Rotational Bands in N $\approx$ Z Nuclei"

Thirteenth International Conference on Defects in Insulating Materials, Winston-Salem, N.C., July 15-19, 1996

Yan, Q., and F. W. Meyer
"Electron Capture from Occupied Surface States within the Band Gap of LiF(100)

Conference on Nuclear Structure at the Limits, Argonne, Ill., July 22-26, 1996

Baktash, C.
"Nuclear Structure Studies with Radioactive Ion Beams at ORNL"

Baktash, C. (Invited Presentation)
"Superdeformation in the Mass A ~ 80 Region"

Davids, C. N., P. J. Woods, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson, D. J. Henderson, R. J. Irvine, J. A. Mackenzie, H. T. Penttila, D. Seweryniak, K. S. Toth, W. B. Walters, and B. E. Zimmerman
"Proton Radioactivity — A Look at Nuclear Structure Beyond the Proton Drip Line"

Dean, D. J. (Invited Presentation)
"Shell Model Monte Carlo Calculations Near N = Z"

Devlin, M., D. R. LaFosse, C. Baktash, I. Birriel, M. J. Brinkman, H.-Q. Jin, I. Y. Lee, F. Lerma, A. O. Macchiavelli, D. Rudolph, J. X. Saladin, D. G. Sarantites, G. N. Sylvan, S. Tabor, D. F. Winchell, V. Q. Wood, and C.-H. Yu
"Second Well Spectroscopy of ^{87}Nb"

Garrett, J. D. (Invited Presentation)
"The Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory"

Garrett, J. D.
"Neutron-Proton Correlations in Self-Conjugate Nuclei"

Garrett, J. D., J. Q. Robinson, A. J. Foglia, and H.-Q. Jin
"Nuclear Level Repulsion and 'Order' vs 'Chaos' "

Jin, H.-Q., C. Baktash, M. J. Brinkman, C. J. Gross, D. Rudolph, C.-H. Yu, I. Birriel, R. M. Clark, M. Devlin, P. Fallon, D. R. LaFosse, I. Y. Lee, F. Lerma, A. O. Macchiavelli, J. X. Saladin, D. G. Sarantites, G. Sylvan, S. L. Tabor, D. Winchell, T. Werner, and V. Wood
"Identical Superdeformed Bands in the A = 80 Region: A Further Probe of Nuclear Deformation"

Jin, H.-Q., and J. D. Garrett
"Distribution of Very-Closely-Spaced Levels with the Same I^{π} in Rare Earth Nuclei"

Jin, H.-Q., C. Baktash, M. J. Brinkman, D. Rudolph, C.-H. Yu, R. M. Clark, M. Devlin, P. Fallon, D. R. LaFosse, I. Y. Lee, F. Lerma, A. O. Macchiavelli, and D. G. Sarantites
"Multiple Superdeformed Bands in Sm Isotopes: Transition from Large Deformation to Superdeformation"

Johnson, N. R., J. C. Wells, Y. A. Akovali, C. Baktash, R. Bengtsson, M. J. Brinkman, D. M. Cullen, C. J. Gross, H.-Q. Jin, I. Y. Lee, A. O. Macchiavelli, F. K. McGowan, W. T. Milner, and C.-H. Yu
"Lifetimes and Deformation-Driving Effects in the $\pi I_{13/2}$ Band of ^{173}Re"

LaFosse, D. R., Y. A. Akovali, C. Baktash, M. Devlin, J. Doring, C. J. Gross, G. D. Johns, I. Y. Lee, F. Lerma, A. O. Macchiavelli, D. Rudolph, D. G. Sarantites, D. W. Stracener, and S. Tabor
"Second Well Spectroscopy of ^{87}Nb"

Lerma, F., S. Asztalos, C. Baktash, M. J. Brinkman, R. M. Clark, M. Devlin, P. Fallon, D. R. LaFosse, I. Y. Lee, A. O. Macchiavelli, R. W. Macleod, and D. G. Sarantites
"Search for Linking Transitions in ^{143}Eu"

Mizutori, S., W. Nazarewicz, W. Satula, J. Dobaczewski, and J. Dudek
"High Spin States in Neutron-Rich Nuclei"

Rudolph, D., C. Baktash, I. Birriel, M. Devlin, H.-Q. Jin, D. R. LaFosse, F. Lerma, J. X. Saladin, D. G. Sarantites, G. Sylvan, S. L. Tabor, D. Winchell, V. Wood, and C.-H. Yu
"Forking and Unusual Decay Out of Superdeformed Bands in ^{83}Zr"

Rudolph, D., C. Baktash, I. Birrel, M. Devlin, C. J. Gross, H.-Q. Jin, D. R. LaFosse, F. Lerma, J. X. Saladin, D. G. Sarantites, W. Satula, G. Sylvan, S. L. Tabor, D. Winchell, V. Wood, and C.-H. Yu
"Systematics of Even-Even T_z = 1 Nuclei in the A = 80 Region: High-Spin Rotational Bands in ^{74}Kr, ^{78}Sr, ^{82}Zr, and ^{86}Mo"

Yu, C.-H., C. H. Baktash, M. J. Brinkman, C. J. Gross, H.-Q. Jin, D. Rudolph, I. Birriel, R. M. Clark, M. Devlin, P. Fallon, D. R. LaFosse, I. Y. Lee, F. Lerma, A. O. Macchiavelli, J. X. Saladin, D. G. Sarantites, G. Sylvan, S. Tabor, J. C. Wells, D. Winchell, and V. Wood
"Lifetime Measurements of Deformed and Superdeformed States in ^{82}Sr"

Zeeman International Conference on Atomic Physics, Amsterdam, Netherlands, Aug. 5-9, 1996

Lee, D. H., W. D. Brandon, D. Nanstorp, and D. J. Pegg
"Photodetachment of C^- Ion"

Fourth Biennial Conference on Low-Energy Antiproton Physics, Dinkelsbuhl, Germany, Aug. 27-31, 1996

Barnes, T. (Invitd Presentation)
"Radial and Orbital $q\bar{q}$ Excitations: 'Higher Quarkonia' "

6th Workshop on Fast Ion-Atom Collisions, Debrecen, Hungary, Sept. 4-6, 1996

Datz, S. (Invited Presentation)
"Atomic Collisions at Ultrarelativistic Energies"

Reinhold, C., J. Burgdorfer, R. Minniti,a nd S. B. Elston (Invited Presentation)
"Solid State Effects in Electron Emission from Atomic Collisions Near Surfaces"

International Workshop on the Identification of Dark Matter, Sheffield, England, Sept. 8-12, 1996

Ressell, M. T. And D. J. Dean (Invited Presentation)
"The Spin-Dependent Neutralino-Nucleus Form Factor for ^{127}I"

4th NEA P&T International Information Exchange Meeting, Mito City, Japan, Sept. 11-13, 1996

Oigawa, H., N. Shinohara, T. Mukaiyama, H. H. Saleh, T. A. Parish, and W. H. Miller
"Recent Measurements of Fission Neutron Yield Data of Minor Actinides"

International Conference on the Physics of Reactors (PHYSOR 96), Mito City, Japan, Sept. 16-20, 1996

Charlton, W. S., T. A. Parish, S. Raman, N. Shinohara, and M. Andoh
"Delayed Neutron Emission Measurements from Fast Fission of U-235 and Np-237"

1996 Erice School: *4π High-Resolution Gamma Ray Spectroscopy and Nuclear Structure*, Erice, Italy, Sept. 16-24, 1996

Baktash, C. (Invited Presentation)
"Nuclear Structure Studies of Medium-Mass Nuclei Using Large Ge Arrays"

International Symposium on Atomic and Molecular Processes in Fusion Plasmas, Nagoya, Japan, Sept. 17-20, 1996

Schultz, D. R., and P. Krstic (Invited Presentation)
"Elastic, Excitation, Ionization and Charge Transfer Cross Sections of Current Interest in Fusion Energy Research"

11th International Workshop on Inelastic Ion Surface Collisions, Wangerooge, Germany, Sept. 22-27, 1996

Hagg, L., C. O. Reinhold, and J. Burgdorfer
"Energy Gain of Highly Charged Ions in Front of LiF"

Meyer, F. W., and Q. Yan (Invited Presentation)
"Projectile Angular Scattering and Charge Equilibration During Grazing Interactions of Multicharged Ions with Au(110) and LiF(100)"

13th International Conference on Electromagnetic Isotope Separators (EMIS-13), Bad Durkeim, Germany, Sept. 23-24, 1996

Alton, G. D., R. F. Welton, and S. N. Murray
"Surface Ionization Source Developments for RIB Generation at the Holifield Radioactive Ion Beam Facility"

Alton, G. D., R. F. Welton, R. Lohwasser, C. Williams, B. Cui, and S. N. Murray
"New Target/Ion Source Concepts for Radioactive Ion Beam Generation"

Alton, G. D., C. L. Williams, and J. W. Middleton
"Design of Composite Target/Heat-Sink Systems for Generation of Radioactive Ion Beams"
Alton, G. D., C. L. Williams, R. F. Welton, and S. N. Murray
"A New Concept, Combined Thermal Dissociator/Electron Impact Ionization Source"

Carter, H. K., J. Kormicki, D. W. Straceberm H, B Breitenbach, J. C. Blackmon, M. S. Smith, and D. W. Bardayan
"First On-Line Results for As and F Beams from HRIBF Target / Ion Sources"

Eighth International Conference on the Physics of Highly Charged Ions (HCI-96), Omiya, Saitama, Japan, Sept. 23-26, 1996

Schultz, D. R., C. O. Reinhold, and P. S. Krstic
"Quasi-Resonant Channel Included Oscillation in Low-Energy Excitation and Ionization of Atoms by Highly Charged Ions"

Vane, C. R., S. Datz, H. F. Krause, H. Knudsen, R. Church, and P. Grafston (Invited Presentation)
"Atomic Collisions with 33-TeV Lead Ions"

Research Conference on Chaotic Phenomena in Nuclear Physics, Heraklion, Crete, Greece, Sept. 29-Oct. 2, 1996

Garrett, J. D. (Invited Presentation)
"Nuclear Level Repulsion, Order vs. Chaos, and Conserved Quantum Numbers"

9. GENERAL INFORMATION

PERSONNEL CHANGES

New Staff Members

B. D. Bryant, United States Navy
D. J. Dean, Wigner Fellow from California Institute of Technology
C. A. Irizarry (transferred from Office of Operational Readiness and Facility Safety)
P. E. Koehler (transferred from Instrumentation and Controls Division)
A. Mezzacappa, University of Tennessee
R. C. Morton, CTI, Knoxville, Tennessee
P. E. Mueller, ORNL Postdoctoral Research Associate
A. H. Poland, Oak Ridge Institute for Science and Education
C. O. Reinhold-Larsson, University of Tennessee
J. W. Sinclair, O. Q. Solutions, Oak Brook, Illinois
J. B. Smith (transferred from Office of Science and Technology Partnerships)
K. A. Sweeton, CTI, Knoxville, Tennessee
C.-H. Yu, University of Rochester

Division Postdoctoral Associates

J. D. Bailey, Michigan State University, East Lansing, Michigan
J. Dellwo, University of Tennessee, Knoxville, Tennessee
E. F. Deveney, University of Connecticut, Storrs, Connecticut
N. Gan, State University of New York, Stony Brook, New York
K. H. Guber, University of Karlsruhe, Karlsruhe, Germany
H. Jin, University of Tennessee, Knoxville, Tennessee
P. K. Joshi, Louisiana State University, Baton Rouge, Louisiana
P. S. Krstic, City College of the City University of New York, New York, New York
E. J. Mansky, Georgia Institute of Technology, Atlanta, Georgia
S. Mizutori, Kyoto University, Kyoto, Japan
P. E. Mueller, University of Illinois, Urbana-Champaign, Illinois
M. W. H. Pieksma, University of Utrecht, Utrecht, the Netherlands
D. Rudolph, University of Gottingen, Gottingen, Germany
P. W. Stankus, Columbia University, New York, New York
D. W. Stracener, Washington University, Saint Louis, Missouri
R. F. Welton, Georgia Institute of Technology, Atlanta, Georgia
W. Wu, Kansas State University, Manhattan, Kansas
Q. Yan, Vanderbilt University, Nashville, Tennessee

Staff Assignments

T. C. Awes, 22-month assignment at CERN, Geneva, Switzerland

Staff Transfers and Terminations

A. Scientific Staff

M. Breinig (retirement)
H. O. Cohn (retirement)
S. B. Elston (retirement)
M. L. Halbert (retirement)
D. J. Horen (retirement)
N. R. Johnson (retirement)
C. M. Jones (retirement)
F. E. Obenshain (retirement)
D. J. Pegg (retirement)
I. A. Sellin (retirement)

B. Administrative and Technical Staff

J. R. Heath (retirement)
K. A. Sweeton (accepted position with CTI, Knoxville, Tennessee)
C. R. Wallace (retirement)

Temporary Assignments

A. Visiting Scientists

M. Akabori, Japan Atomic Energy Research Institute, Tokai-mura, Japan
D. An, Institute of High Energy Physics, Beijing, People's Republic of China, and University of Tennessee, Knoxville, Tennessee
J. C. Batchelder, Oak Ridge Associated Universities, Oak Ridge, Tennessee
J. C. Blackmon, University of North Carolina, Chapel Hill, North Carolina
J. B. Breitenbach, Oak Ridge Associated Universities, Oak Ridge, Tennessee
Y. V. Efremenko, University of Tennessee, Knoxville, Tennessee
S. L. Fokine, Kurchatov Institute of Atomic Energy, Moscow, Russia
B. Gervais, Commissariat a l'Energie Atomique, Paris, France
C. J. Gross, Oak Ridge Associated Universities, Oak Ridge, Tennessee
M. Gupta, University of Bombay, Bombay, India
L. M. Hagg, Uppsala University, Uppsala, Sweden
A. Ichihara, Japan Atomic Energy Research Institute, Tokai-mura, Japan
J. W. Johnson, Oak Ridge Associated Universities, Oak Ridge, Tennessee
D. B. Khrebtukov, University of Tennessee, Knoxville, Tennessee
J. Kormicki, Vanderbilt University, Nashville, Tennessee
M. D. Kovarik, University of Tennessee, Knoxville, Tennessee
A. L. Lebedev, Kurchatov Institute of Atomic Energy, Moscow, Russia
H. P. P. Lebius, University of Tennessee, Knoxville, Tennessee
D-H. Lee, University of Tennessee, Knoxville, Tennessee
Q. Li, Institute of High Energy Physics, Beijing, People's Republic of China
Q. Liu, Institute of High Energy Physics, Beijing, People's Republic of China
P. F. Mantica, Oak Ridge Associated Universities, Oak Ridge, Tennessee
A. Mezzacappa, University of Tennessee, Knoxville, Tennessee
D. P. Morrison, University of Tennessee, Knoxville, Tennessee
W. Nazarewicz, University of Tennessee, Knoxville, Tennessee

A. Visiting Scientists (continued)

S. A. Nikolaev, Kurchatov Institute of Atomic Energy, Moscow, Russia
F. E. Obenshain, University of Tennessee, Knoxville, Tennessee
D. V. Onoprienko, University of Tennessee, Knoxville, Tennessee
S. Ovchinnikov, University of Tennessee, Knoxville, Tennessee
P. E. Raison, Commissariat a l'Energie Atomique, Paris, France
C. O. Reinhold-Larsson, University of Tennessee, Knoxville, Tennessee
T. Sato, Japan Atomic Energy Research Institute, Tokai-mura, Japan
W. Shi, Fudan University, Shanghai, People's Republic of China
N. Shinohara, Japan Atomic Energy Research Institute, Tokai-mura, Japan
Y. Sun, University of Tennessee, Knoxville, Tennessee
R. Xu, Institute of High Energy Physics, Beijing, People's Republic of China, and University of Tennessee, Knoxville, Tennessee
Y. Wan, China Institute of Atomic Energy, Beijing, People's Republic of China
J. F. D. Wauters, Katholieke University, Leuven, Belgium
R. A. F. Wehlitz, Fritz-Haber-Institute, Berlin, Germany
T. R. Werner, University of Warsaw, Warsaw, Poland
Y. Zhao, University of Tennessee, Knoxville, Tennessee

B. Graduate Students

D. W. Bardayan, Yale University, New Haven, Connecticut
W. D. Brandon, University of Tennessee, Knoxville, Tennessee
Y. M. Butt, Yale University, New Haven, Connecticut
A. C. Calder, Vanderbilt University, Nashville, Tennessee
S. A. Deutscher, University of Tennessee, Knoxville, Tennessee
T. N. Ginter, Vanderbilt University, Nashville, Tennessee
G. Han, Institute of High Energy Physics, Beijing, People's Republic of China
S. A. Held, University of Rochester, Rochester, New York
M. J. Hicks, University of Tennessee, Knoxville, Tennessee
A. Huang, University of Tennessee, Knoxville, Tennessee
P. Klasnja, University of Tennessee, Knoxville, Tennessee
J. G. Kreke, University of Tennessee, Knoxville, Tennessee
J. Y. Lim, University of Tennessee, Knoxville, Tennessee
A. Maysam, University of Tennessee, Knoxville, Tennessee
J. W. Middleton, Mississippi State University, Mississippi State, Mississippi
R. Minniti, University of Tennessee, Knoxville, Tennessee
S. Mioduszewski, University of Tennessee, Knoxville, Tennessee
T. Misu, University of Tennessee, Knoxville, Tennessee
M. M. G-H. Mostafa, Ain Shams University, Cairo, Egypt
D. H. Olive, Jr., Vanderbilt University, Nashville, Tennessee
D. Onoprienko, University of Tennessee, Knoxville, Tennessee
I. M. Qashou, University of Tennessee, Knoxville, Tennessee
Y. Qiu, University of Tennessee, Knoxville, Tennessee
K. S. Salovaara, Royal Institute of Technology, Stockholm, Sweden
F. W. Segner, University of Frankfurt, Frankfurt, Germany
M. Seng, University of Tennessee, Knoxville, Tennessee
K. D. Shmakov, University of Tennessee, Knoxville, Tennessee
K. D. Sorge, University of Tennessee, Knoxville, Tennessee
L. B. Straus, University of Tennessee, Knoxville, Tennessee
A. G. Wig, University of Tennessee, Knoxville, Tennessee

C. Joint Institute for Heavy Ion Research (JIHIR) Guests (at ORNL for at least six months)

J. L. Blankenship, Self
X. Chen, Institute of Nuclear Research, Shanghai, People's Republic of China
B. Cui, University of Tennessee, Knoxville, Tennessee
J. J. Das, Nuclear Science Center, New Delhi, India
G. Di Bartolo, Instituto Nazionale di Fisica Nucleare, Catania, Italy
M. K. Gupta, University of Bombay, Bombay, India
J. A. Harvey, Self
S. Kahane, Nuclear Research Center-Negev, Beersheva, Israel
Y. A. Kamyshkov, Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
K. Kaneko, Kyushu Sangyo University, Fukuoka, Japan
H. J. Kim, Self
F. K. McGowan, Self
C. W. Nestor, University of Tennessee, Knoxville, Tennessee
S. Rab, Kuwait Institute for Scientific Research, Kuwait, Kuwait
W. Satula, University of Warsaw, Warsaw, Poland
M. R. Schmorak, Self
E. Stein, University of Frankfurt, Frankfurt, Germany
W. Tian, China Institute of Atomic Energy, Beijing, People's Republic of China
N. Zeldes, Hebrew University of Jerusalem, Jerusalem, Isael
J. Zhang, University of Tennessee, Knoxville, Tennessee

D. Department of Energy (DOE) Research Internship/Technical Leadership Development Program

B. H. Cain, U.S. Department of Energy, Washington, D.C.

E. Historically Black Colleges and Universities (HBCU) Faculty Research Participation Program

C. Hung, Alabama A&M University, Normal, Alabama

F. Oak Ridge Associated Universities (ORAU) Graduate Student Research Participation Program

G. Y. Poe, Georgia Institute of Technology, Atlanta, Georgia

Undergraduate Assignments

A. Science and Engineering Research Semester (SERS) Participants

D. T. Becher, University of Nebraska, Lincoln, Nebraska
M. F. Crudele, Rensselaer Polytechnic Institute, Troy, New York
J. F. Mas, Manatee Community College, Bradenton, Florida
M. E. Minear, Cornell University, Ithaca, New York
J. L. Mosher, Bryn Mawr College, Bryn Mawr, Pennsylvania
J. Q. Robinson, University of Kentucky, Lexington, Kentucky
H. D. Sanders, Cornell University, Ithaca, New York

B. Southeastern Universities Research Association (SURA) Participants

R. A. Jarvis, University of Connecticut, Storrs, Connecticut
G. A. MacLachlan, University of Connecticut, Storrs, Connecticut

C. Oak Ridge Institute for Science and Education (ORISE) Professional Internship Progam

A. J. Foglia, Dartmouth College, Hanover, New Hampshire

D. Great Lakes Colleges Association/Associated Colleges of the Midwest (GLCA/ACM) Science Program Participants

E. A. Chowdhury, Wabash College, Crawfordsville, Indiana
R. J. Grow, Colorado College, Colorado Springs, Colorado

E. Individual Student Research Participants

S. R. Bombarger, University of Tennessee, Knoxville, Tennessee
K. J. Roche, University of Tennessee, Knoxville, Tennessee

F. University of Tennessee/ORNL Science Alliance Undergraduate Program Participants

M. M. Abdelrazek, University of Tennessee, Knoxville, Tennessee
C. A. Brindle, University of Tennessee, Knoxville, Tennessee
D. A. Dolgov, Moscow Institute of Physics and Technology, Moscow, Russia
K. M. Friesen, Bethel College, North Newton, Kansas
J. A. Gary, University of Missouri, Rolla, Missouri
J. J. Kuropatwinski, University of Tennessee, Knoxville, Tennessee
K. D. Sorge, Hastings College, Hastings, Nebraska
C. T. Tracy, Rose-Hulman Institute of Technology, Terre Haute, Indiana

INFORMATION MEETING

The most recent Physics Division Information Meeting was held on May 1-3, 1995. The members of the Advisory Committee were:

S. M. Austin, Michigan State University
P. D. Bond, Brookhaven National Laboratory
C. L. Cocke, Jr., Kansas State University
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PHYSICS DIVISION SEMINARS: OCTOBER 1994–SEPTEMBER 1996

Seminars arranged by the Physics Division and announced in the ORNL Technical Calendar are listed below. During the period of this report, S. (Ram) Raman served as Seminar Chairman.

1994

Oct. 13	Joachim A. Maruhn University of Frankfurt Frankfurt, Germany	Heavy-Ion-Induced Fusion
Oct. 24	Helge Ravn CERN, Geneva, Switzerland	New Radioactive Ion Beam Developments at ISOLDE
Oct. 27	Rainer W. Novotny University of Giessen, Germany	Mesons: A Probe for Hot and Dense Nuclear Matter
Nov. 2	Aurel Sandulescu Romanian Academy, Bucharest	Cluster Radioactivity: Solitons, Breathers, and Cold Fission
Nov. 10	Masumi Oshima Japan Atomic Energy Research Institute, Tokai-mura	Two-Phonon Gamma Vibrational States in Well-Deformed Nuclei
Dec. 8	Bernard Haas Center for Nuclear Research Strasbourg, France	Superdeformation in the Rare-Earth Region Studied with EUROGAM
Dec. 15	Herbert Faust Institut Laue-Langevin, Grenoble France	Radioactive Beam Project PIAFE

1995

Jan. 12	Nissan Zeldes Hebrew University of Jerusalem Israel	Shell-Model Interpretation of Nuclear Masses
Jan. 26	Tony Mezzacappa University of Tennessee Knoxville	Core Collapse Supernovae: Studies in One and Three Dimensions
Feb. 7	Burkhard Fricke University of Kassel Germany	Inner-Shell Excitation in Ion-Atom and Ion-Solid Collisions
Feb. 9	Giovanni Ciavola Istituto Nazionale Fisica Nucleare Catania, Italy	Radioactive Ion Beam Facility EXCYT
Feb. 20	Daniel Savin University of California Berkeley, California	X-Ray Astrophysics: Iron *L*-Shell Emission in Collisionally Dominated Plasmas

Mar. 9	Victor Janzen Chalk River Nuclear Laboratories Ontario, Canada	High-Spin Physics with the 8π Spectrometer
Mar. 16	Alexander W. Riedy K-25 Site National Security Program Office, Oak Ridge	Project Sapphire: Secret Mission To Remove Highly Enriched Uranium
Apr. 6	Vitali Shoutko Institute for Theoretical & Experimental Physics Moscow	Search for New Particles with L3 Detector at LEP-I and Beyond
May 18	V. M. Mikoushkin A. F. Ioffe Physico Technical Institute, St. Petersburg, Russia	Size Transformation of Electronic Properties of Small Ag Clusters Supported by Inert Surfaces
May 25	Ian Thompson University of Surrey United Kingdom	Structure and Reactions of Halo Nuclei
June 27	Krzysztof Rykaczewski University of Warsaw, Poland	Decay Studies Near Doubly Magic ^{100}Sn
June 29	Helmut Leeb University of Wien, Austria	Basic and Applied Research with Neutrons
July 6	Neil Rowley University of Manchester, England	Quantal Tunneling in Nuclear Physics
July 18	Santo Gammino Istituto Nazional Fisica Nucleare Catania, Italy	Radioactive Ion Beam Facility at INFN
July 20	Terry Awes ORNL Physics Division	Electromagnetic Probes of High-Density Matter
July 27	Sven Åberg Lund Institute of Technology Sweden	Diffusion in Complex Quantal Systems
Aug. 3	Peter D. Parker Yale University, New Haven Connecticut	Explosive Nucleosynthesis in Stars
Aug. 8	Pertti Tikkanen University of Helsinki, Finland	Use of Inverse Reactions in Lifetime Measurements
Aug. 10	Hermann Wollnik Universität Giessen, Germany	Direct Mass Measurements of Cooled Au and Bi Projectile Fragments
Aug. 17	Cheng-Li Wu Chung Yuan Christian University Chung-Li, Taiwan	Nuclear Masses and Stability of Superheavy Elements

Aug. 31	Steve Lamoreaux University of Washington, Seattle	Prospects for Measuring Neutron Lifetime and Electric Dipole Moment with Ultracold Neutrons
Sept. 29	Walter Greiner Universität Frankfurt, Germany	Extension of the Periodic Table of New Sectors of Strangeness and Antimatter
Nov. 2	William L. Talbert ORNL Physics Division, Oak Ridge Los Alamos, New Mexico	Technical Issues in Producing Accelerated Radioactive Beams
Nov. 20	Suehiro Takeuchi Japan Atomic Energy Research Inst. Tokai-mura, Japan	Tandem-Injected Superconducting rf Post Accelerator

<u>**1996**</u>

Jan. 11	Art Champagne University of North Carolina Chapel Hill, North Carolina	Nuclear Probes of Stellar Evolution
Jan. 16	Victor Ninov GSI, Darmstadt, Germany	Synthesis of Heavy and Superheavy Elements
Jan. 31	Krzysztof Rykaczewski University of Warsaw, Poland	Decay Studies Near ^{100}Sn
Feb. 20	Bill Appleton ORNL Cental Management	Plans for a New Spallation Source at Oak Ridge
Feb. 22	Guy Savard Chalk River Nuclear Laboratories Ontario, Canada	Penning Trap as a Mass Spectrometer for Unstable Isotopes
Mar. 7	Moshe Gai University of Connecticut Storrs, Connecticut	Nuclear Astrophysics with Secondary Radioactive Beams
Mar. 19	Karl Langanke Caltech, Pasadena, California	Recent Progress and Future Perspectives in Nuclear Astrophysics
April 4	J. Michael Ramsey ORNL Chemical and Analytical Sciences Division	Microfabrication of Chemical Measurement Systems
May 9	Klaus Bongardt KFA-Julich, Germany	European Spallation Source
May 10	Fredrich Aumayr Vienna Technical University Austria	Interaction of Highly Charged Ions with Surfaces
June 11	Abdelouahad Chbihi GANIL, Caen, France	Recent Results from INDRA

June 12	Paul Stankus Oak Ridge Institute for Science and Education	Direct Photon Production in High-Energy Heavy-Ion Collisions
June 27	Bo Cederwall Royal Institute of Technology Stockholm	Studies of Nuclei Near the Proton Drip Line: From Nordball to Euroball
July 2	Franz Käppeler Forschungszentrum Karlsruhe Germany	*s*-Process Branchings in the Rare-Earth Region
July 18	Cheuk-Yin Wong ORNL Division Staff	Anomalous J/Ψ Suppression as a Signal for the Quark-Gluon Plasma
July 30	Vincent Cianciolo Lawrence Livermore National Laboratory, California	Understanding Heavy-Ion Collisions
Aug. 8	Grant Matthews University of Notre Dame Indiana	Instabilities in Close Neutron Star Binaries
Aug. 13	Paul-Henri Heenen University of Brussels Belgium	Mean-Field Description of Exotic Deformed Nuclei
Aug. 15	John D. Vergados University of Ioannina Greece	Supersymmetric Dark Matter
Aug. 26	Ron Soltz Lawrence Livermore National Lab. Livermore, California	Hadronic Probes of the Quark-Gluon Plasma
Aug. 29	Yosio Kondo University of Tokyo Tokyo, Japan	Quasimolecular Description of Resonant Structures in $^{16}O+^{12}C$
Sept. 25	Petr Vogel Caltech Pasadena, California	Neutrino-Induced Reactions and Supernova *r*-Process Nucleosynthesis

SCIENTIFIC MEETINGS HELD DURING THIS PERIOD

Workshop on Atomic Physics and Plasma Modeling of Edge/Divertor Plasmas
Oak Ridge, Tennessee, October 28-29, 1994

D. R. Schultz and C. F. F. Karney (Princeton), organizers

Discussions on Detectors for the Focal Plan of the RMS
Oak Ridge, Tennessee, December 1-3, 1994

C. J. Gross, organizer

PHENIX Collaboration Meeting
Oak Ridge, Tennessee, May 24-26, 1995

F. Plasil and K. F. Read, organizers

HRIBF Users Workshop
Oak Ridge, Tennessee, June 2-3, 1995

C. J. Gross, organizer

Workshop on Data Analysis
Oak Ridge, Tennessee, February 7-10, 1996

H-Q. Jin and W. Reviol (U. Tennessee), organizers

International Workshop on Future Prospects of Baryon Instability Search in p-Decay and n-$\bar{n}$ Oscillation Experiments
Oak Ridge, Tennessee, March 28-30, 1996

W. M. Bugg (U. Tennessee), Yu. Kamyshkov (ORNL and U. Tennessee), R. Mohapatra (U. Maryland), and F. Plasil, organizers

Workshop on Atomic Physics in Fusion and Astrophysics and Its Implementation in the Atomic Data and Analysis Structure (ADAS)
Oak Ridge, Tennessee, August 8-9, 1996

D. R. Schultz, M. S. Pindzola (Auburn U.), and H. Summers (Strathclyde U., U.K.), organizers

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