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INTRODUCTION

This report covers the research and development activities of the Physics Division for the 1990 fiscal year, beginning October 1, 1989, and ending September 30, 1990. The activities of this Division continue to be concentrated in the areas of experimental nuclear physics, experimental atomic physics, and theoretical nuclear and atomic physics.

The Holifield Heavy Ion Research Facility and its operation as a national user facility continued as the single largest activity within the Division. This year's operations were, however, reduced from previous years as a result of budget limitations. Despite these limitations, accelerator performance continued to improve with notable achievements including extended operation at top voltages, a number of new ion species provided for experiments, and first coupled beams of calcium and lead isotopes. These and other highlights are summarized in Chapter 1.

The experimental nuclear physics program continues to emphasize heavy ion studies, with much of the activity centered at the Holifield Facility. During this past year, these studies have seen an increased emphasis on various aspects of nuclear structure. The higher energy reaction spectroscopy studies have also utilized beams from the GANIL facility, particularly for studies of giant resonance phenomena. Results from the past year's work are included in Chapter 2.

The work with heavy ions at ultrarelativistic energies continues at the CERN SPS. Studies at the Brookhaven AGS, particularly in preparation for future experiments at RHIC, have seen an increased emphasis. A major consortium has been formed to propose the design and construction of a dimuon detector as the basis for one of the principal experiments for RHIC. Results of this work are presented in Chapter 3. Also included in this chapter are results from the increasing effort in particle physics, including participation in the L* proposal for the SSC.

The UNISOR program, since its inception, has been associated intimately with the Division and, most particularly, with the Holifield Facility. A summary of the research of this consortium is included in Chapter 4.

A major area of experimental research for the Division is atomic physics. This activity comprises two groups: one on accelerator-based atomic physics, centered primarily at the EN-tandem and the Holifield Facility, but extending this year to an experiment at ultrarelativistic energies at the CERN SPS; and one on 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 5. Included in this section is also a description of a new effort in multicharged ion-surface interactions, and details of a planned upgrade of the ECR source.

The Division efforts in the development of Tokamak diagnostics for the Fusion Energy program are described in the work of the Laser and Electro-Optics Lab summarized in Chapter 6.

The theoretical physics activity in the Division concentrates on the areas of atomic physics, nuclear physics, and physics at the nuclear-particle interface. These efforts, which represent independent studies as well as support to the experimental program, are presented in Chapter 7. Included in this chapter are the results of work associated with the Center for Computational Intensive Physics.

The Division operates two efforts 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 8.

A major new initiative for the Division is the proposal for a radioactive ion beam capability for the Holifield Facility. Details of this study and the proposed upgrade are described in Chapter 9.

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

J. B. Ball
March 1991

1. HOLIFIELD HEAVY ION RESEARCH FACILITY

OVERVIEW

R. L. Robinson and C. M. Jones

Due to a significant decrease in the fiscal year 1990 operating budget, it was necessary, beginning January 1, 1990, to reduce the operations staff and the number of operating hours for the accelerators. For the remainder of the fiscal year, the accelerators operated on a two-week schedule of 31 shifts for research followed by an 11-shift budgetary shutdown. Even with this restriction, the high reliability of the tandem accelerator made it possible to provide 4093 research hours in FY 1990 (for comparison, 4829 research hours were provided in FY 1989). The greater impact was on coupled operation, which only accounted for 677 hours in FY 1990 as compared with 1110 hours in FY 1989.

In contrast to the fewer research hours permitted by budget constraints, the number of hours being requested in proposals submitted to the Program Advisory Committee has increased. During the three most recent Program Advisory Committee meetings, the average number of hours requested was near 3700 as compared to the mid-2000s only two years ago. Consequently, only about half of the requested hours can be approved, with the result that many good experiments cannot be undertaken.

The research hours for fiscal year 1990 were distributed among 56 runs which met, in part, the research needs of 178 scientists from 47 institutions (see Table 1.1). Of these, 54 were students.

Highlights of the accelerator system include:

Routine operation continued with potentials on the tandem terminal up to 24.4 MV.

During one experiment, the tandem accelerator was operated with terminal potentials between 23.7 and 23.9 MV for over 11 days with only 7 tank sparks.

The first coupled operation experiment was performed with a ^{40}Ca beam. The energy was 15 MeV/nucleon.

New beams of ^{148}Nd and ^{150}Sm were provided for research. These rare earth beams were produced in the coupled mode at 700 MeV.

A 982-MeV ^{208}Pb beam was developed and used for research. This is the heaviest ion species used for nuclear physics studies at the Holifield.

Since the Gammasphere Siting Committee in 1989 recommended the Holifield as the preferred site for the Gammasphere, a conceptual design of a new target room for both the Gammasphere and the Recoil Mass Spectrometer (RMS) was prepared. Design for the RMS was finalized early in 1990; the bids were received recently and are now being evaluated.

To address an important need in this country, the Joint Institute for Heavy Ion Research initiated an effort to develop a nuclear structure theory center. This center will become even more important as the RMS and Gammasphere become operational. A key component of this effort has been the filling this year of a permanent nuclear structure theory position with UNISOR. The Joint Institute currently supports a postdoctoral position in this area and a number of nuclear structure theory guests (22 in FY 1990 for a total effort of two work-years). Beginning in January, another senior physicist will be supported by the Joint Institute. Already this effort is beginning to impact research directions at the Holifield.

A major new initiative under consideration by the Holifield Facility is a modification of the accelerator system to produce radioactive beams with reasonable intensities (some greater than 1 pnA). It is estimated that this modification will have a modest cost (\$3.5M), a short (3-year) completion time, and that it will produce radioactive beams up to mass 80 with sufficient energy for nuclear physics research. These beams can be used to produce more than 200 new proton-rich compound systems. This initiative is discussed in Section 9 of this report.

Table 1.1. Distribution of users who participated in research programs at the Holifield during the twelve-month period between October 1, 1989, and September 30, 1990

Institution	Number of Researchers	Institution	Number of Researchers
U.S. UNIVERSITIES		NATIONAL LABORATORIES	
Berea College	2	Argonne National Laboratory	2
Eastern Kentucky University	1	Idaho National Energy Laboratory	2
Furman University	2	Lawrence Livermore National Laboratory	3
Georgia State University	2	NASA	5
Georgia Institute of Technology	5	Oak Ridge National Laboratory	32
Louisiana State University	5		
Michigan State University	5		44
Mississippi State University	3		
Oak Ridge Associated Universities	4	NON-U.S. INSTITUTIONS	
Oregon State University	3	CEN/Saclay (France)	1
State University of New York	1	CNEA (Argentina)	1
Tennessee Technological University	2	CRN (France)	2
Texas A&M University	5	GSI/Darmstadt (Germany)	1
University of Kentucky	3	KFA/Julich (Germany)	1
University of Maryland	9	Oxford University (United Kingdom)	4
University of North Carolina	1	Ruder Boskovic Inst. (Yugoslavia)	1
University of Pittsburgh	2	University of Frankfurt (Germany)	1
University of Rochester	10	University of Gent (Belgium)	1
University of the South	1	University of Heidelberg (Germany)	2
University of Tennessee	11	University of Kyoto (Japan)	1
Vanderbilt University	18	University of Leuven (Belgium)	1
Washington University	4	University of Liverpool (United Kingdom)	2
Western Kentucky University	3	University of Mexico (Mexico)	3
Yale University	2	University of Osaka (Japan)	2
	104	University of Sussex (United Kingdom)	2
		University of Tokyo (Japan)	3
		University of York (United Kingdom)	1
			30
		Total	178

ACCELERATOR OPERATIONS

<i>G. D. Alton</i>	<i>C. A. Ludemann</i>
<i>M. R. Dinehart</i>	<i>R. L. McPherson</i>
<i>D. T. Dowling</i>	<i>J. A. Martin¹</i>
<i>H. D. Hackler</i>	<i>M. J. Meigs²</i>
<i>C. L. Haley</i>	<i>G. D. Mills</i>
<i>D. L. Haynes</i>	<i>S. W. Mosko</i>
<i>C. A. Irizarry</i>	<i>S. N. Murray</i>
<i>C. M. Jones</i>	<i>D. K. Olsen</i>
<i>R. C. Juras</i>	<i>B. K. Sizemore</i>
<i>S. N. Lane</i>	<i>B. A. Tatum</i>
<i>C. T. LeCroy</i>	<i>S. D. Taylor</i>
<i>N. F. Ziegler¹</i>	

The most notable aspect of accelerator operations was the change from full-time to part-time operation which was required in response to a reduction in funding for facility operation. While it was possible to operate the accelerators full time for the first three months of the fiscal year, it was then necessary to use a ten-day-up, four-day-down cycle for the remaining nine months. It was also necessary to suspend operations for all holidays. As a result, the total beam provided for research decreased from 4829 hours in FY 1989 to 4093 hours in FY 1990. Correspondingly, the number of research hours provided with coupled operation decreased from 1110 hours in FY 1989 to 677 hours in FY 1990. In spite of this intrinsically less efficient operating schedule, total unscheduled maintenance as a fraction of total beam hours available for research was maintained at a level (8.6%) comparable to the average of the three preceding fiscal years. Complete operating statistics for FY 1990 are shown in Tables 1.2 and 1.3.

A list of beams provided for research in FY 1990 is given in Table 1.4. During this period, beams of 27 ion species were provided, four for the first time. Several of these beams were especially notable. The 601-MeV ^{40}Ca beam was the first attempt to provide a coupled operation beam with this difficult ion species. The 701-MeV ^{148}Nd and 698-MeV ^{150}Sm beams further demonstrated the capability of the facility to provide rare earth beams at energies appropriate for nuclear physics measurements using separated isotope ion source samples. The 982-MeV ^{208}Pb beam is the heaviest beam accelerated to energies appropriate for nuclear physics measurements and the first coupled operation beam developed using foil stripping in the tandem terminal.

Other important work related to operations included completion of modifications to the integrated radiation safety system, implementation of a new surveillance procedure for this system, completion of a new badge reader system for controlling building entry by the general public, and completion of the first phase of preparation of new facility safety documentation.

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1. Consultant.
 2. Instrumentation and Controls Division, ORNL.

TANDEM ACCELERATOR

<i>G. D. Alton</i>	<i>R. L. McPherson</i>
<i>D. L. Haynes</i>	<i>M. J. Meigs¹</i>
<i>C. M. Jones</i>	<i>G. D. Mills</i>
<i>R. C. Juras</i>	<i>N. F. Ziegler²</i>

Voltage Performance

Routine operation of the tandem accelerator at terminal potentials up to 24.4 MV continued during FY 1990 without difficulty or any apparent spark-induced damage. During one period beginning in January 1990, the accelerator was operated for 268 hours at terminal potentials between 23.7 and 23.9 MV with seven full-column sparks. The observed spark frequency of 2.6 sparks/100 hours is consistent with our previous observations when operating in this voltage range.

An important observation concerns recovery of the acceleration tubes after exposure to air. After 22 uninterrupted months under vacuum (with one brief exception), the acceleration tubes were exposed to room air for approximately seven days during installation of the auxiliary gas containment valves described in last year's report.³ Recovery of normal voltage performance after this exposure was quite rapid. After approximately one month of operation for the experimental program and only 85 total hours of conditioning, stable operation at 23.0 MV was easily demonstrated.

Voltage performance is now limited by inhomogeneous voltage grading which is believed to be associated with worn corona points. After replacement of the corona points in January 1991, an effort will be made to increase the routine voltage operating limit from 24 MV to approximately 25 MV.

Table 1.2. Tandem accelerator utilization for the period October 1, 1989, through September 30, 1990

	Hours	Percent
Beam available for research (tandem-alone and coupled operation)	4093	47
Beam available during ORIC tuning (coupled operation)	373	4
Accelerator tuning (includes scheduled startup-shutdown)	521	6
Machine studies (includes conditioning not required for specific experiments)	452	5
Total operating time	5439	62
Unscheduled maintenance	121	1
Scheduled maintenance	1276	15
Scheduled shutdown	1924	22

Table 1.3. Cyclotron utilization for the period October 1, 1989, through September 30, 1990

	Hours	Percent
Beam available for research (coupled operation)	677	8
Accelerator tuning (includes scheduled startup-shutdown and operation during tandem tuning)	220	2
Machine studies	82	1
Total operating time	979	11
Unscheduled maintenance	229	3
Scheduled shutdown and maintenance	7552	86

Table 1.4. Beams provided for research for the period October 1, 1989, through September 30, 1990

Ion Species	Maximum Energy (MeV)	Mode [†]
¹ H	25	T
¹¹ B	56	T
¹² C	155	T
¹⁶ O	360	T,C
¹⁷ O	376	C
¹⁸ O	101	T
²⁴ Mg	175	T
²⁶ Mg	133	T
²⁷ Al	145	T
²⁸ Si	245	T
³¹ P*	140	T
³² S	250	T
³⁶ S	175	T
³⁵ Cl	195	T
³⁷ Cl	160	T
⁴⁰ Ca	601	T,C
⁴⁵ Sc	205	T
⁴⁸ Ti	350	T
⁵⁶ Fe	400	T
⁵⁸ Ni	340	T
⁷⁹ Br	929	C
⁸⁰ Se	340	T
¹⁴⁸ Nd*	701	C
¹⁵⁰ Sm*	698	C
¹⁹⁷ Au	550	T
²⁰⁸ Pb*	982	C

* Provided for first time in FY 1990.

[†] T = Tandem alone; C = coupled mode.

Operation

Reliability of the tandem accelerator continued to be excellent. Unscheduled maintenance for the period was 121 hours, or 3% of beam-on-target time. This fraction sets a new facility record for the second straight year. Significantly, this is the first year in which there were no interruptions of the experimental program by unscheduled tank openings. Of the six tank openings in this period, four were scheduled and two were unscheduled. Fortunately, the unscheduled tank openings immediately followed scheduled tank openings and did not affect the experimental program.

Operation of the SF₆ storage and recirculation system continued to be without incident. SF₆ inventory losses for the year were about 1.5%.

Improvements and Modifications

As described in other contributions to this report, work on improvements to the tandem accelerator system continued. Important parts of this work include development of an improved ion source ionizer heater, design of a new freon-cooled ion source housing, and development of a new terminal foil stripper mechanism which is expected to significantly improve terminal foil lifetime.

1. Instrumentation and Controls Division, ORNL.
2. Consultant.
3. *Phys. Div. Prog. Rept. for Period Ending Sept. 30, 1989*, ORNL-6578, p. 8.

ORIC ACCELERATOR

A. M. H. Basher ¹	S. W. Mosko
D. T. Dowling	D. K. Olsen
S. N. Lane	B. A. Tatum

During the 12-month period of this report, 10 separate heavy ion beams were produced in coupled operation of ORIC and the tandem accelerator. These beams are summarized in Table 1.5. Noteworthy beams were: (1) the 15-MeV/nucleon ⁴⁰Ca beam, the first coupled beam with a calcium isotope; (2) the 4.7-MeV/nucleon ¹⁴⁸Nd and ¹⁵⁰Sm rare earth beams; and (3) the 4.7-MeV/nucleon ²⁰⁸Pb beams, the heaviest mass accelerated to date above the Coulomb barrier and the first coupled beam using foil stripping in the tandem terminal.

ORIC was scheduled for 1208 hours of operation in FY 1990. Of this time, 759 hours, or 63%, was available for physics research and beam development, 220 hours, or 18%, was used for tuning, and 229 hours, or 19%, was used for unscheduled maintenance. The increased unscheduled maintenance time for FY 1990 resulted mostly from various commissioning problems with the Dynapower power supply for the inside coil of the lower channel. These problems have now been resolved.

A particularly significant achievement occurred on January 16, 1990, when a 981.7-MeV (4.72-MeV/nucleon) ²⁰⁸Pb beam was produced by the

HHIRF accelerator system and used to Coulomb excite a ¹⁵⁹Tb target. The resulting γ rays were observed with an array of 20 Compton-shielded Ge detectors in coincidence with recoiling Tb nuclei impinging on six Si detectors. The lead beam was accelerated in the 44+ charge state through ORIC, operating at K = 125. ORIC was injected with a 412-MeV 17+ beam from the tandem accelerator operated at 23 MV. The tandem was injected with 165 nA of PbO⁻ from a PbO probe. Prior to the experimental run, the tandem transmission, terminal-foil charge-state fractions, and foil lifetimes for both PbO and PbO₂ beams, as well as the ORIC injection-foil charge-state-fractions were all measured. About 1 nA of beam was available on target, giving a coincidence rate of 30 events/s. A total of 1.1×10^6 coincidences were collected over a 10-hour run.

ORIC Development

ORIC Beam Emittance Measurement.

Measurements of the ORIC beam emittance were completed using a 375-MeV ¹⁷O⁸⁺ beam. Two methods were employed using two phosphor-coated viewers marked with concentric rings and viewed with TV cameras. One viewer was located just beyond the first quadrupole doublet under the ORIC resonator and the second was located 3.2 m further down the beam line. A waist was formed on the first viewer and the beam was allowed to expand onto the second viewer. Emittance was estimated from the horizontal and vertical dimensions of the two beam spots and the viewer separation distance. The measurements were repeated by forming a waist on the second viewer and again examining beam spot dimensions on both viewers. It was determined that at least 90% of the ORIC beam was contained in an emittance of 4π mm-mrads in both the horizontal and vertical planes.

Control System Enhancements. Renovation of the ORIC control system continued. The central section of the control console was reorganized and modernized for improved tuning efficiency and operator training. On/off controls for the compensated magnetic channel outside coil power supply were permanently moved to the ORIC control computer. Obsolete controls and wiring were removed from the control room and cyclotron vault.

Table 1.5. Coupled operation for research from October 1, 1989, to September 30, 1990

Date	Ion	Desired Energy (MeV)	Measured Energy (MeV)	Error (%)	Beam on Target (onA)	Tandem Voltage (MV)	Injected Charge State	Injected Energy (MeV)
10/17/89	$^{17}\text{O}^{8+}$	375.0	375.4	0.1	125	19.3	3+	77
11/12/89	$^{40}\text{Ca}^{16+}$	600.0	600.8	0.1	20	20.5	5+	123
1/16/90	$^{208}\text{Pb}^{44+}$	977.0	981.7	0.5	1.0	22.9	17+	412
2/23/90	$^{148}\text{Nd}^{32+}$	700.0	700.6	0.1	25	23.8	8+	209
3/2/90	$^{150}\text{Sm}^{32+}$	700.0	698.3	0.2	40	23.8	8+	209
3/21/90	$^{17}\text{O}^{8+}$	375.0	375.3	0.1	80	22.3	3+	90
3/28/90	$^{208}\text{Pb}^{44+}$	977.0			0.5	22.9	17+	412
5/24/90	$^{79}\text{Br}^{27+}$	930.0	929.4	0.1	5	20.4	9+	209
6/2/90	$^{17}\text{O}^{8+}$	375.0	375.9	0.2	50	22.3	3+	90
6/8/90	$^{16}\text{O}^{8+}$	352.9	360.0	2.0	15	22.3	3+	90

Magnet Power Supplies. The new 3000-A, 60-V power supply for the inside coil of the compensated-magnetic channel in the extraction system experienced serious component failures early in the year. Diode protection was added to the pass transistor banks to protect from spikes due to coupling with the channel's outside coil and ORIC's main field. This permitted operation up to 67% of rated current. Poor performance at higher currents was caused by inadequate cooling which was corrected by increasing water flow and adding cooling fans to the front and rear sections of the supply.

Beam Line Developments

Beam Line Upgrade AIM Project. The AIM project for replacement of some of the ORIC area beam lines was approved by DOE. Preliminary design work continued in anticipation of receiving the FY 1990 funds which were delayed for NEPA documentation and approval.

Beam Line Hardware. Replacement of the vacuum chamber for beam switching magnet 4 was completed. This magnet is utilized to transport coupled beams to the Spin Spectrometer, 1.6-meter

chamber, and UNISOR, and will be utilized for transporting coupled beams to the Gammasphere and the RMS. A new cryopump system, beam diagnostic chamber, and beam viewer were also installed at the exit of the magnet. The normal operating vacuum in this region was improved from approximately 5×10^{-5} Torr to 5×10^{-8} Torr.

Vacuum Control System. The new ORIC beam line vacuum control system was brought into routine operation. Additional ion gauge controllers were added to beam line sectors and experiment stations. Control of additional gate valves was implemented and work is currently under way to add beam viewers to the system.

Facility Development

Deionized Water System. The HHIRF deionized water system was modified to reduce resin bed regeneration frequency and improve environmental compliance. The makeup water to the system is now taken from the facility's steam condensate waste stream instead of the potable water supply. The condensate has a typical conductivity level of 3 micromhos, whereas the potable water

supply is usually about 70 micromhos. The deionizer's resin beds which then reduce conductivity to less than 1 micromho, can now operate for substantially longer periods without regeneration. This reduces the large quantities of waste water produced by the regeneration process which must be transported to a treatment facility.

Radiation Safety System. Integration of the radiation safety systems of the ORIC and the tandem accelerator was completed. ORIC now has three experiment rooms which are operated in the controlled-entry mode, as are all tandem areas. The ORIC vault and two remaining rooms are operated in their original total-exclusion mode. An extra circuit was added to the Radiation Safety System that identifies unenergized or malfunctioning radiation detectors and provides appropriate system warnings and interruptions. A single quarterly safety check procedure was implemented for the inspection and testing of the integrated system.

HISTRAP RF Control System

A prototype frequency control system was developed for the HISTRAP accelerating system. An analog signal derived from the field intensity in one sector magnet was converted to a digital signal that updated the setting of a digitally controllable frequency synthesizer at frequent intervals throughout acceleration or deceleration cycles. The update intervals were typically of the order of 10 microseconds, but could be as short as one microsecond.

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TERMINAL STRIPPER FOIL LIFETIME TESTS

*R. L. Auble N. L. Jones
C. M. Jones D. K. Olsen*

Motivated by the importance of terminal stripper foil lifetime in coupled-operation accelerator system performance with very heavy ions, a careful study of effective foil lifetimes with 20.3-MeV ^{197}Au beams was performed. Initially, this work was directed primarily towards understanding the significance of a new foil fabrication technique reported by Dollinger

and Maier-Komor of the Technical University of Munich at the 1989 Symposium of Northeastern Accelerator Personnel.¹ Specifically, the Munich group reported that carbon foils prepared using laser heating of carbon samples to very high temperatures ($\sim 300,000\text{K}$) exhibited lifetimes under heavy ion bombardment of the order of ten times longer than predicted by the lifetime formula of Auble and Galbraith.² Later, the scope of the study was expanded to include an investigation of the dependence of effective foil lifetime on foil thickness, as well as several accelerator operating parameters which influence the density profile of the beam incident on the foil.

The measurements to be described were performed with foils mounted in the tandem accelerator high-voltage terminal. ^{197}Au beams were injected into the tandem accelerator while operating with a terminal potential of 20.0 MV and the 15+ charge state was chosen for subsequent acceleration. With an injected beam energy of 0.3 MeV, this gives a final energy of 320.3 MeV. Since it is believed that the terminal entrance Faraday cup may not read correctly due to incomplete secondary electron suppression, the measurements were expressed in terms of accelerated beam intensity which can be accurately measured. Specifically, the results are expressed in terms of an effective lifetime L defined as

$$L = Q_0/Q_p \quad (1)$$

In this expression, Q_0 is the total beam charge (proportional to fluence) measured by a Faraday cup which intercepts the energy-analyzed accelerated beam. For each foil, Q_0 was measured over a time interval during which the accelerated beam intensity decreased from the initial value to one-half the initial value. The predicted charge Q_p was calculated from the expression $Q_p = F_A \cdot \text{TRANS} \cdot C_Q \cdot Q$ where F_A is the foil lifetime predicted for unslackened glow-discharge carbon foils using the formula of Auble and Galbraith,² TRANS is the empirical, ion-mass-dependent transmission factor used for performance modeling (0.261), C_Q is the measured charge state fraction (18.5%) for charge 15, and Q is the selected charge state (15). F_A is given by

$$F_A(\mu\text{A}\cdot\text{min}) = AE(0.73T-1.0)/Z^2M \times 10^4 \quad (2)$$

where A = beam spot area (mm^2),
 E = beam energy (MeV),
 Z = beam atomic number,
 M = beam ion mass, and
 T = foil thickness ($\mu\text{g}/\text{cm}^2$).

Since there is a significant dependence of F_A on foil thickness, it is important to know the thickness of tested foils. In this case, approximate relative foil thicknesses were determined in an ancillary measurement in which small-angle Rutherford scattering yields were measured for 25-MeV ^{197}Au beams incident on foils of the same type as those used in the terminal measurements.

Carbon foils from three sources were used in these measurements: (1) Foils obtained from the Munich group, (2) commercial foils obtained from the Atomic Energy Canada Limited facility at Chalk River, and (3) foils fabricated at the Holifield facility. The Munich foils were fabricated using both the new laser heating technique¹ and conventional vapor deposition. In agreement with previous observations,³ the foils prepared by vapor deposition exhibited short lifetimes and will not be discussed further in this report. Both the Chalk River and Oak Ridge foils were fabricated by deposition from a glow discharge in an ethylene-argon gas mixture. The Munich foils and foils used for comparison to the Munich foils were mounted on 9.5-mm-inside-diameter frames. In tests using these foils, a 3.2-mm-diameter aperture was positioned in front of the foil. Other foils were mounted on 15.9-mm-inside-diameter frames. In tests using these foils, apertures of either 3.2-mm or 9.6-mm diameter were positioned in front of the foils. All of the foils were slackened. Foil thicknesses were in the range 3 to 7 $\mu\text{g}/\text{cm}^2$.

The results of these measurements may be briefly summarized as follows:

(1) If it is assumed (a) that the diameter of the beam entering the terminal is about 4 mm, so that the effective beam area with the 9.6-mm aperture is $\pi(4)^2/4 = 12.6 \text{ mm}^2$ and the effective beam area with the 3.2-mm aperture is $\pi(3.2)^2/4 = 8.0 \text{ mm}^2$, and (b) that, in agreement with previous measurements, the effect of slackening is a lifetime improvement of a factor of three,³ then the measured values of L are generally greater than or equal to the values which would be predicted using Eq. 2. It is believed that the "greater than" values may correspond to foils in which stress relieving tears occurred outside the spot illuminated by the beam.

(2) The dependence of measured L values on foil thickness is in good agreement with Eq. 2. That is, the measured L values increase with increasing foil thickness. Since the accelerator transmission efficiency, accelerated beam intensity/injected beam intensity, decreases only slowly with increasing foil thickness, it is thus generally better to use thicker foils unless the injected beam intensity is limited by other considerations such as ion source performance.

(3) There is little, if any, dependence of the measured L values on injected beam intensity or the size of the variable aperture used in the injector.

(4) The lifetime performance, as defined by Eq. 1, of the Munich foils prepared by laser heating is no better than that of foils of comparable thickness prepared by the glow-discharge technique. In view of the complexity and expense of the laser-heating technique, this method appears to have no advantage.

1. G. Dollinger and P. Maier-Komor, *Proc. 1989 Symposium of Northeastern Accelerator Personnel, Oak Ridge, Tennessee (October 1989)*, p. 138.

2. R. L. Auble and D. M. Galbraith, *Proc. 1980 Symposium of Northeastern Accelerator Personnel, Madison, Wisconsin (October 1980)*, p. 228.

3. R. L. Auble, J. K. Bair, D. M. Galbraith, C. M. Jones, P. H. Stelson, and D. C. Weisser, *Nucl. Instr. and Meth.* 177, 289 (1980).

IMPROVED RELIABILITY CESIUM SURFACE IONIZERS

G. D. Alton and G. D. Mills

In order to improve reliability, reduce cost, and avoid excessively long delivery times, new spiral-wound, coaxial Ta ionizer heating elements were designed for use in standard spherical, ellipsoidal, and cylindrical-geometry negative ion sources. The effort was primarily motivated by a large number of failures of the original W ionizers, principally due to internal shorting of the W-Re heating elements. The original ionizers were expensive and, more importantly, required very long lead times for manufacture and delivery. The new ionizer design can be constructed quickly, in house, from commercially available coaxial Ta wire. Figure 1.1 schematically displays the ionization region of a

standard source¹⁻⁴ equipped with a spiral-wound, coaxial cesium surface ionizer.

Experience gained during routine HHIRF operation has demonstrated good reliability, while negative ion yields appear to be comparable to those produced in sources equipped with the original W ionizer.²⁻⁴ Perhaps the most significant gain derived from the new ionizer design is that upon failure due to breakage or shorting new ionizers can be quickly and inexpensively replaced.

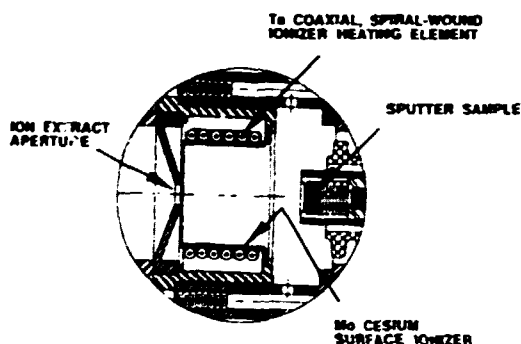


Fig. 1.1. Schematic display of the ionization region of a standard source equipped with a spiral-wound, coaxial-cesium surface ionizer.

1. G. D. Alton et al., *Phys. Div. Prog. Report for Period Ending Sept. 30, 1986*, ORNL-6326, p. 7.
2. G. D. Alton, *Nucl. Instr. and Meth. A244* (1986).
3. G. D. Alton and G. D. Mills, *IEEE Trans. Nucl. Sci. NS-32* (5), 1822 (1985).
4. G. D. Alton and J. W. McConnell, *Nucl. Instr. and Meth. A268*, 445 (1988).

MODIFICATIONS TO STANDARD CESIUM SPUTTER NEGATIVE ION SOURCE

G. D. Alton and G. D. Mills

During the fiscal year, a new freon-cooled housing was designed for future use in conjunction with standard cesium sputter negative ion sources.¹⁻³ The source, equipped with the previously discussed spiral-wound, coaxial cylindrical-geometry ionizer and new freon-cooled housing, is displayed in

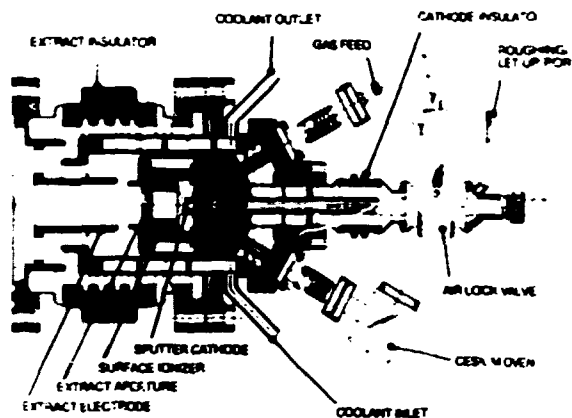


Fig. 1.2. Schematic of standard cesium sputter negative ion source equipped with spiral-wound, coaxial ionizer heating element and re-entrant freon-cooled housing.

Fig. 1.2. The re-entrant housing design was incorporated in an effort to protect the high-voltage insulator from neutral cesium buildup which ultimately leads to high extract current drains and, consequently, to reduced operational source lifetime between cleanings. The new housing design should, in principle, greatly extend the lifetime of the source between cleanings because the high-voltage insulator is not directly exposed to cesium emitted from the source aperture. The design, as well, shortens the length of the source by some 73 mm over that of the original source.¹⁻³ The housing is presently under construction and will be employed in all standard cesium-sputter negative ion sources as soon as it becomes available.

1. G. D. Alton, *Nucl. Instr. and Meth. A244* (1986).
2. G. D. Alton and G. D. Mills, *IEEE Trans. Nucl. Sci. NS-32* (5), 1822 (1985).
3. G. D. Alton and G. D. McConnell, *Nucl. Instr. and Meth. A268*, 445 (1988).

COMPUTER SIMULATION OF THE OPTICS OF THE AXIAL-GEOMETRY, PLASMA-SPUTTER, HEAVY NEGATIVE ION SOURCE

G. D. Alton

During the fiscal year, computer simulation studies of the ion extraction region of the axial-geometry, plasma-sputter, heavy negative ion source¹ were continued. These studies were initiated to evaluate the effects of space charge on beam phase space growth and to arrive at an electrode design with focal properties commensurate with good beam transport during ion extraction from the source. Since the source is capable of generating peak beam intensities of several mA, the emittance of beams such as Au^- , Cu^- , and Pt^- is expected to be dominated by space charge effects.

The ion optics of the ion generation and extraction region of the extraction electrode system were studied computationally through use of the code described in Ref. 2 for Au^- beam intensities of 1 to 10 mA in increments of 1 mA. Examples of such calculations are shown in Fig. 1.3, which displays ion trajectories for a 1-mA Au^- or a 3.5-mA O^- , and in Fig. 1.4 for a 3-mA Au^- or a 10.5-mA O^- beam generated at the sputter probe surface and accelerated through the field-free region of the plasma and finally into the extraction lens system at energies up to 51 keV. As noted, space charge effects result in rapid growth of the size and angular divergence of the beam as it exits the plasma region and enters into the post-acceleration field of the electrode system. The effects are even more dramatic at higher beam intensities.

1. G. D. Alton, *Phys. Div. Prog. Report for Period Ending Sept. 30, 1989*, ORNL-6578, p. 11.

2. J. H. Whealton, *Nucl. Instr. and Meth.* **189**, 55 (1981).

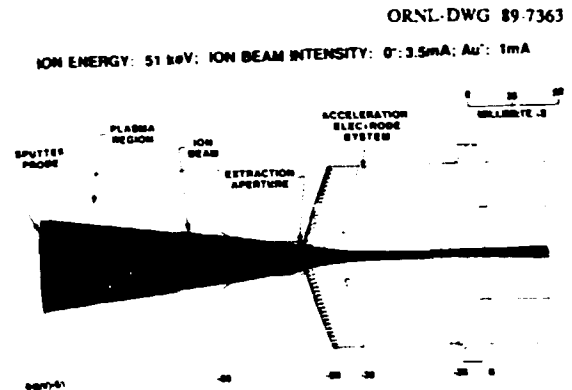


Fig. 1.3. Negative ion optics of the axial-geometry, sputter, heavy negative ion source equipped with a two-stage extraction electrode system for a 1-mA beam of Au^- or a 3-mA beam of O^- .

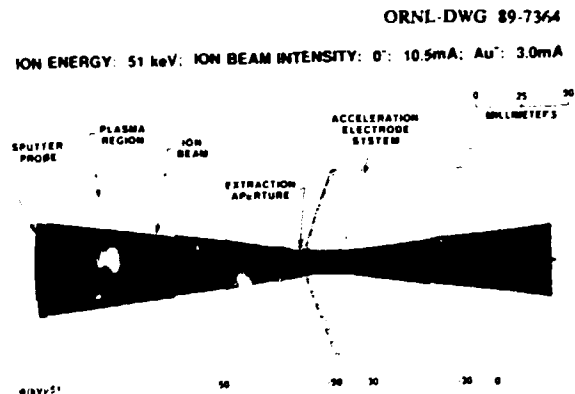


Fig. 1.4. Negative ion optics of the axial-geometry, sputter, heavy negative ion source equipped with a two-stage extraction electrode system for a 3-mA beam of Au^- or a 10.5-mA beam of O^- .

PULSED PLASMA DISCHARGE POWER SUPPLY FOR THE HIGH-INTENSITY PLASMA SPUTTER SOURCE

G. D. Alton and G.K. Schulze¹

During this fiscal year, a pulsed-mode, current-regulated power supply was designed and fabricated, and is presently under test and evaluation. The supply will be used for igniting and sustaining the pulsed plasma discharge of the high-intensity, plasma-sputter, negative ion source.² After ignition, the plasma will rise and fall according to the pulse width and repetition rate required for proposed HISTRAP³ synchrotron injection applications.

The pulsed-mode, plasma-discharge power supply, shown schematically in Fig. 1.5, will be used to set and control parameters required for pulsing the plasma discharge in synchronism with the injection application. The parameters include the following:

Current: 0 to 50 A with regulation $\leq 1\%$.
 Pulse width: digitally adjustable from 2 to 50 μs .
 Pulse rate: digitally adjustable from 0.2 to 50 pulses/s from an internal or external trigger.

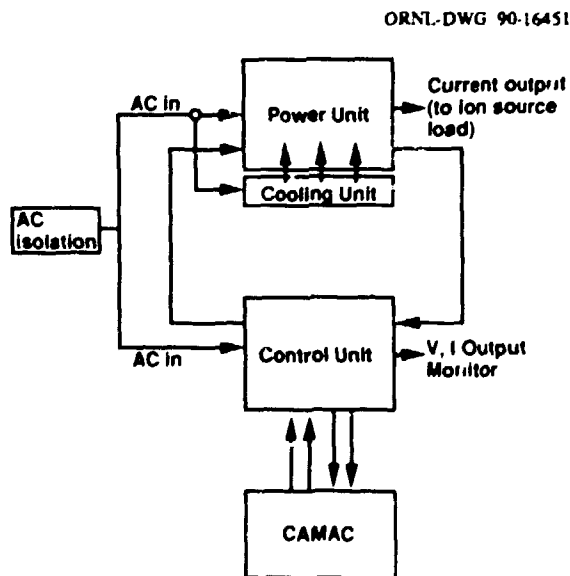


Fig. 1.5. Schematic drawing of pulse-mode, plasma-discharge power supply.

The power supply consists of two basic units: a control/logic unit and a power unit. The control unit

functions are generated by simple digital logic which generates an analog level and digital gating signal for driving the power unit. Provisions have also been made to control the power supply via CAMAC at some later time.

The power unit which powers the plasma discharge is composed of two supplies which are combined in parallel through protective diodes. The first is a power unit which supplies current for the duration of the pulse while the second functions as an igniter. The igniter power supply is used as an "arc striker." It consists of a single high-voltage rated MOSFET connected in series with a much higher voltage and the LaB_6 cathode electron emitter. At the leading edge of the pulse, the circuit is gated on to provide an impulse of high voltage from a storage capacitor to accomplish ignition.

1. Instrumentation and Controls Division, ORNL.

2. G. D. Alton, *Phys. Div. Prog. Report for Period Ending Sept. 30, 1989*, ORNL-6578, p. 11.

3. D. K. Olsen et al., "The HISTRAP Proposal: Heavy Ion Storage Ring for Atomic Physics," *Nucl. Instr. and Meth. B* 24/25, 26 (1987).

FEASIBILITY STUDIES FOR AN ELECTRON-CYCLOTRON RESONANCE PLASMA STRIPPER

G. D. Alton and R. E. Olson¹

During the fiscal year, a plasma stripping method was proposed which, if successful, could offer an alternate to both gaseous and foil stripping for stripping heavy ions to higher charge states, approaching those of a carbon foil, while preserving the infinite lifetime and beam quality of a gaseous stripper. The concept is based on the results of preliminary atomic physics calculations which suggest that by proper selection of the stripper species, an ionized medium can potentially yield higher equilibrium projectile charge states than a neutral stripper. The device would utilize electron cyclotron resonance (ECR) heating of electrons confined magnetically in a long solenoidal magnetic field (~ 1 m) to produce the highly ionized medium ($\sim 10^{13}/\text{cm}^3$) for stripping electrons from heavy ion projectiles during transit through the device.

A series of calculations was performed for 20-MeV Pb^{+q} ions incident on a nitrogen plasma target in charge states $j = 0$ to $j = +4$. The electron capture cross sections were calculated using the n-body classical-trajectory Monte Carlo (nCTMC) method.² This theoretical procedure explicitly follows the motion of the projectile ion, target nucleus, and target electrons through an ensemble of scattering events. It provides a method for simultaneously determining the angular distributions and energies of the recoil target ion, the projectile ion, and the ejected electrons.

The results of the electron capture and stripping cross-section calculations for 20-MeV Pb^{+q} are shown in Fig. 1.6. Equilibrium is assumed to occur at the charge state value where the electron capture and projectile stripping cross sections are equal. The equilibrium charge states for 20-MeV Pb on carbon reach a value of +15.

Efforts will be continued during the coming fiscal year to develop a more complete model which includes projectile excited state production and the cross sections for stripping out of these levels with ECR electrons. Other strippers for stripping 20- to 25-MeV Pb projectiles such as members of the group IA and group IIA elements are also being evaluated.

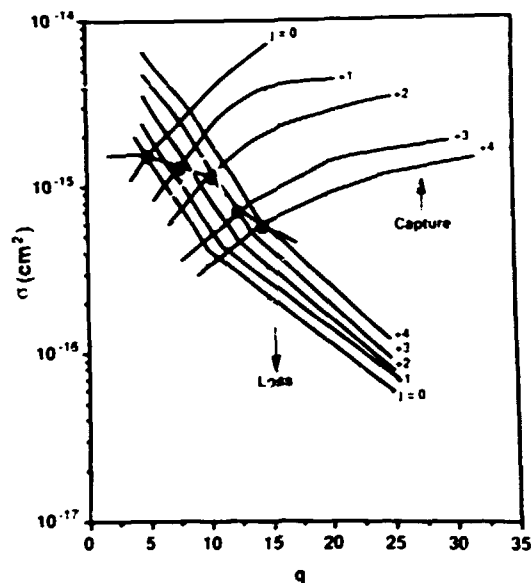


Fig. 1.6. Results of electron capture and stripping cross-section calculations for 20-MeV Pb^{+q} on a N target in various charge states j .

1. Consultant, University of Missouri, Rolla, Missouri.

2. R. E. Olson, *Electronic and Atomic Collisions*, ed. H. B. Gilbody, W. R. Newell, F. H. Read, and A. C. H. Smith, Elsevier (1988) pp. 271-285.

DEVELOPMENT OF A NEW TANDEM ACCELERATOR TERMINAL FOIL STRIPPER MECHANISM

D. L. Haynes R. C. Juras
C. M. Jones M. J. Meigs¹

Analyses of accelerator system performance show that improved terminal stripper foil lifetime can lead to significant improvements in accelerated beam intensity and energy, especially for the heaviest beams provided with coupled operation. In fact, it seems clear that improved terminal stripper foil lifetime is almost certainly the most cost-effective way to improve accelerator system performance.

Accordingly, a new foil stripper mechanism has been designed and constructed. As shown in Fig. 1.7, this mechanism has the capability of moving foils in a circular path in a plane perpendicular to the beam. In the present design, a radius of 3 mm was chosen for this circular motion. With a nominal beam spot size of 4-mm diameter, use of this mechanism will increase the foil area illuminated by the beam from $4\pi \text{ mm}^2$ to $24\pi \text{ mm}^2$, a factor of six.

A number of important criteria were considered in the design of this mechanism. These included:

- Use of a standard National Electrostatics Corporation 200-position flexible foil frame belt.
- Direct replacement compatibility with the existing foil mechanism housing.
- Independent circular and foil indexing motions.
- Three options for circular motion (continuous, incremental in four positions, off).
- Reliable foil indexing.
- Convenient foil position adjustment after installation.
- Convenient control and monitoring via the existing CAMAC-based control system.
- All-metal, high-vacuum-compatible construction.

All of these criteria were satisfied in the present design.

Assembly of the mechanism was completed in August 1990. After functional testing, it will be installed in the tandem accelerator in January 1991.

¹ Instrumentation and Controls Division, ORNL.

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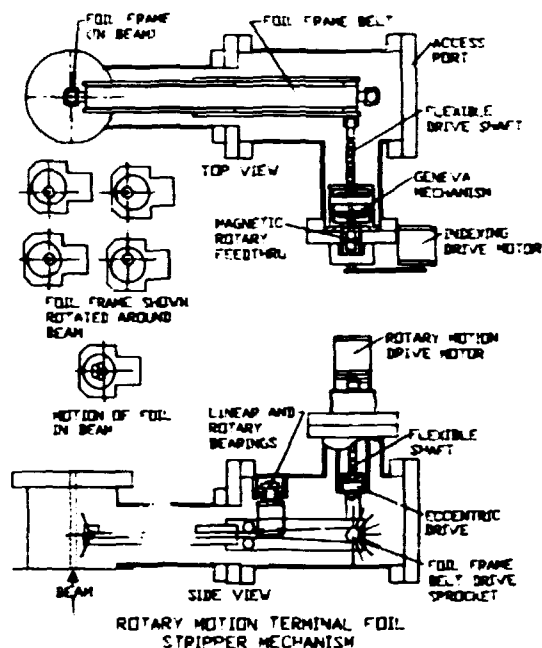


Fig. 1.7. A simplified schematic drawing of the circular-motion foil-stripper mechanism which has been fabricated for installation in the tandem accelerator terminal.

ECR SOURCE FOR THE HHIRF TANDEM ACCELERATOR

<i>D. K. Olsen</i>	<i>R. C. Juras</i>
<i>G. D. Alton</i>	<i>S. N. Lane</i>
<i>D. T. Dowling</i>	<i>M. J. Meigs¹</i>
<i>D. L. Haynes</i>	<i>G. D. Mills</i>
<i>C. M. Jones</i>	<i>S. W. Mosko</i>
<i>B. A. Tatum</i>	

The installation in the HHIRF tandem accelerator terminal of a NEOMAFIOS-type² all-permanent-magnet ECR source has been studied. Both the performance improvement and engineering feasibility of such an installation were considered.

Improved Performance

An ECR source could possibly be advantageous if larger currents of higher charge states could be obtained in the tandem terminal than with conventional negative ion injection. The most interesting cases are for very heavy ions which are foil stripped, where the maximum beam current in the terminal is limited by foil lifetime considerations.

Figure 1.8 shows a comparison for a ^{208}Pb beam where the expected current available in the high-voltage terminal for acceleration through the high-energy tube is plotted as a function of charge state. Results for six cases are shown. The three lower curves are for tandem accelerators with foil strippers and operated at terminal voltages of 6, 12, and 24 MV. The upper curves are for terminal ECR sources. Results for three ECR sources are shown: (1) Measured Bi currents from the all-permanent magnet, lower power, compact, 8-GHz NEOMAFIOS source;² (2) Measured Au currents from the ORNL 10.6-GHz source previously described;³ and (3) Measured Bi currents from the large, high-power, 6.4-GHz LBL source.⁴ As the terminal voltage increases from 6 to 24 MV, the peak charge state for an equilibrium distribution from foil strippers increases from 9 to 17 and the corresponding beam energy increases from 0.29 to 2.16 MeV/nucleon. Equally important, the higher beam energy for stripping increases the foil lifetime and hence current from 10 pA to 35 pA. For the results of Fig. 1.8, a foil lifetime of 30 minutes was required, assuming beam-current-lifetime products estimated for 5 $\mu\text{g}/\text{cm}^2$ -thick, glow-discharge foils from the work of Auble et al.⁵ Clearly, the beam

currents available from foil stripping are foil-lifetime limited.

A lead beam with an energy between 4.5 and 6.0 MeV/nucleon, and an intensity between 0.1 and 1.0 pA, is of great interest for nuclear structure physics and cannot be produced with existing electrostatic accelerators. Such a lead beam at the HHIRF can be accelerated using the ORIC as an energy booster. The product of the transmission, foil fraction, and bunching factor through ORIC is about 5%. Consequently, to deliver 1 pA of beam on target would require about 40 pA of lead in the tandem terminal to inject into ORIC, assuming a 50% beam loss in the tandem high-energy tube. As shown in Fig. 1.8, 40 pA of lead cannot be obtained in the tandem terminal at 24 MV with the present foil lifetime limits. However, the three ECR sources produce at least 40 pA of beam for ORIC injection.

The determination of the ORIC output energy from this beam is somewhat complicated. The maximum energy from ORIC is determined by the charge state from the injection foil, which is energy-dependent and determined by the tandem energy which, in turn, is determined by the tandem terminal charge state. These relationships are illustrated for ^{208}Pb in Fig. 1.9, which shows the maximum ORIC current as a function of energy. Five curves are shown: conventional tandem operation with a terminal gas stripper, conventional tandem operation with a terminal foil stripper, and tandem operation with a terminal ECR source using the NEOMAFIOS, ORNL, and LBL current results. The numbers on the curves give the terminal charge state, whereas the bottom scale gives the ORIC charge state. The energy range of interest for nuclear structure physics is also shown. Clearly, the installation of a terminal ECR source would allow the HHIRF coupled accelerators to produce lead beams for nuclear structure physics with intensities above one pA.

Engineering Feasibility

There are many factors to consider in the installation of an ECR source in the tandem terminal, among which are space, weight, power, cooling, vacuum, control, bunching, reliability, and beam optics requirements. The solutions to some of these problems have been studied. The power constraints in the tandem terminal require an all-permanent-magnet, NEOMAFIOS-type source. The 722-lb magnetic structure of this source is fabricated

entirely of NdFeB permanent magnets and is designed for resonance at 8 GHz, $B = 0.29$ T, a frequency for which powerful air-cooled microwave generators exist. About 0.8 kW of rf power is required and the total power consumption for the source is less than about 3 kW. The ECR chamber is 8 cm in diameter, 15 cm long, is a single-stage device, and is vacuum pumped only through the extraction electrode. Measured beam currents from this source are used in this study.²

The beam transport system from the ECR source would select a single charge state prior to injection into the high-energy tube of the tandem accelerator. A possible system, shown in Fig. 1.10, would transport the expected 30π mm-mrad-MeV^{1/2} emittance from the source into the corresponding 96π mm-mrad-MeV^{1/2} acceptance of the high-energy tube. The source potential would be at 50 kV positive with respect to the terminal voltage, with a variable energy 10 kV extraction electrode. An einzel lens would focus the beam from the source to the object point of a 40-cm radius, 110°, double-focusing dipole magnet with end angles of 35.5° and focal length of 56 cm. Variable apertures and Faraday cups would be located at both the object and image positions of this magnet. An electrostatic mirror would bend the ions by 90° to merge the beam into the existing tandem terminal optics system. With the voltage of the electrostatic mirror off and the ECR transport system valved off, the tandem accelerator would operate without interruption with normal negative ion injection.

Figure 1.11 shows the ECR source and beam transport system in the tandem terminal mounted in a horizontal plane above the highest casting. This ECR system is estimated to have an installed weight of less than 11,000 pounds and would require less than 30 kW of the 38 kW of power available. Also shown in Fig. 1.11, directly below the electrostatic mirror, is a double-drift bunching system which would be used to prepare the ECR beam for the $\pm 3^\circ$ phase acceptance of ORIC.

DISCUSSION

It should be fully appreciated that the motivation for installing an ECR source in the HHIRF tandem terminal would be to produce, in coupled operation, very heavy beams with energies above 4.5 MeV/nucleon with intensities of the order of 1 pA. Presently, such beams are foil-lifetime-limited, with negative ion injection using the foil

lifetime estimates of Auble et al.⁵ for $5 \mu\text{g}/\text{cm}^2$ thick, flow-discharge foils. The results shown in Figs. 1.8 and 1.9 are based on this assumption.

Improvements in foil lifetimes may also be possible. Measurements made in the terminal of the tandem accelerator operating at 20 MV with a gold beam indicate that a small increase in foil thickness, from about 5 to $7 \mu\text{g}/\text{cm}^2$, can significantly increase foil lifetime without serious degradation of beam quality and transmission. In addition, a new foil changer has been developed for the HHIRF tandem accelerator which will allow the foil to be rotated in a 6-mm-diameter circle, thus increasing the effective area of the beam spot on the foil by about a factor of six. With these two changes, an improvement in foil lifetime of at least a factor of 4.5 may be possible. A determination of the achievable foil lifetime with these two improvements will be made in the near future.

1. Instrumentation and Controls Division, ORNL.
2. G. Melin et al., *Proc. of Int. Conf. on the Physics of Multiply Charged Ions and Int. Workshop on ECR Ion Sources, Grenoble (1988)* p. 573; private communication, R. Geller, December 1989.
3. F. W. Meyer and J. W. Hale, *Proc. 1987 IELE Particle Accelerator Conference, Washington, DC (1987)* p. 319.
4. D. J. Clark and C. M. Lyncis, *Proc. of Int. Conf. on the Physics of Multiply Charged Ions and Int. Workshop on ECR Ion Sources, Grenoble (1988)* p. 759.
5. R. L. Auble and D. M. Galbraith, *Nucl. Instr. and Meth.* 200, 13 (1982).

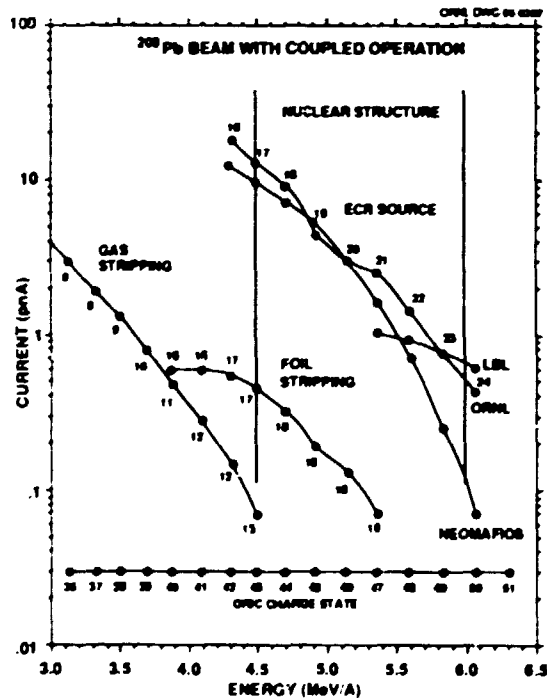
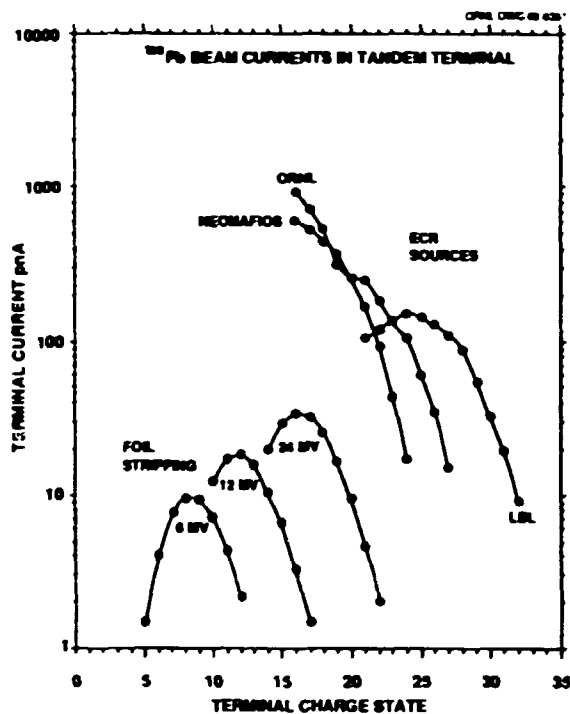


Fig. 1.8. Comparison of expected ^{208}Pb beam currents in the terminal of a tandem accelerator between conventional negative ion injection with foil stripping and three terminal ECR sources.

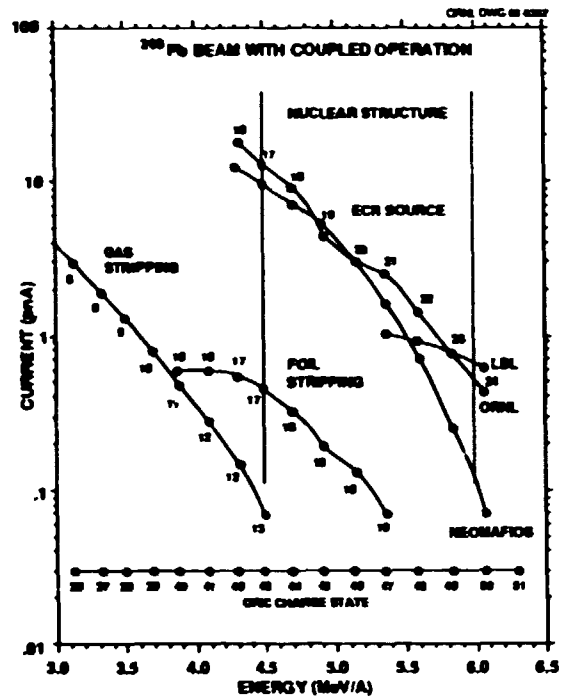


Fig. 1.9. Expected ^{208}Pb beam currents from ORIC in coupled operation. Results for the tandem operated at 24 MV with either gas or foil single stripping are shown, as well as results for the NEOMAFIOS, ORNL, and LBL ECR sources mounted in the tandem terminal. The charge states in the tandem terminal are listed along the curves, whereas the ORIC charge states for $K = 105$ are given on the bottom of the figure.

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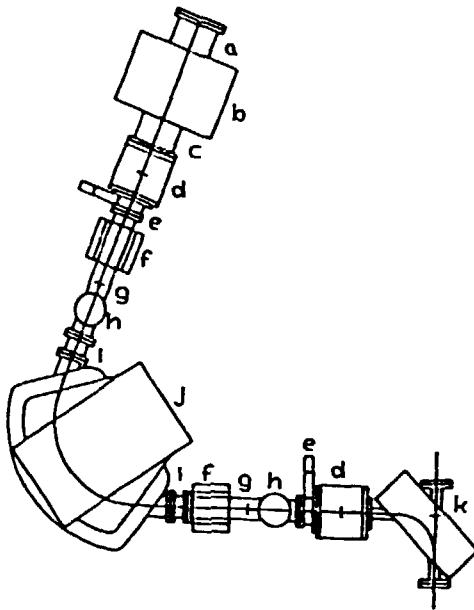
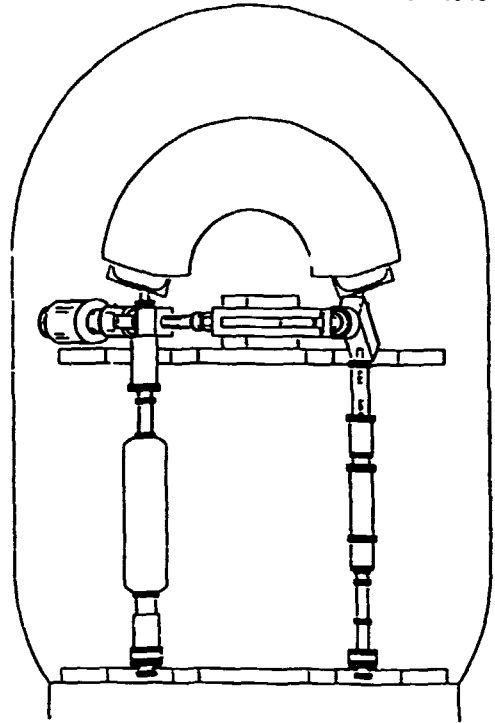


Fig. 1.10. HHIRF tandem terminal ECR source consisting of: a) material, rf, water and power feeds; b) ECR chamber and permanent magnet structure; c) extraction and acceleration electrodes and vacuum manifold; d) einzel lens; e) valve; f) magnetic steerer; g) variable aperture and Faraday cup at 110° dipole focus; h) pumping tee; i) bellows; j) 110° dipole magnet; and k) 90° electrostatic mirror.

ORNL-DWG 90-16563



ORNL-DWG 90-16562

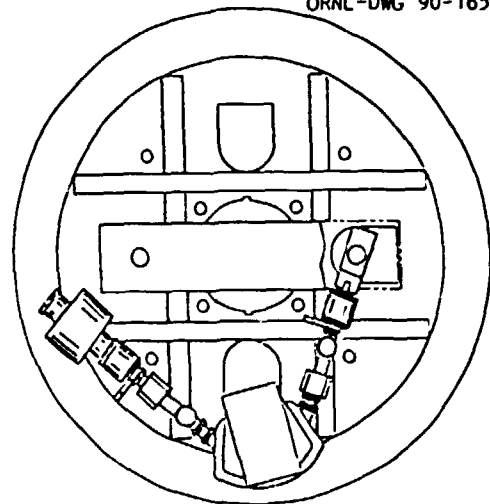


Fig. 1.11. Top and side view of the 3.9-m-diameter terminal of the HHIRF tandem accelerator. The ECR source and beam transport system are shown positioned in a horizontal plane above the top casting of the accelerator. Beam is injected into the high-energy tube with a 90° electrostatic mirror.

BAR-CODE BADGE READER

R. C. Juras *R. L. McPherson*
*C. A. Ludemann*¹ *C. E. Mitchell*²

In response to Department of Energy criteria for the determination of facility hazard levels, a new badge-reader entry system was developed for Building 6000. In order for the Holifield facility to be considered a low-hazard facility, the potential for radiation exposure to members of the general public must be much less than the radiation exposure limits for employees and visitors. The intent of the badge-reader system is to prevent inadvertent entry by members of the general public into the accelerator facility while at the same time allowing convenient access by anyone possessing a Martin Marietta Energy Systems badge.

In contrast to the centrally controlled magnetic badge readers used in many other Energy Systems facilities, the Holifield facility badge-reader system uses the bar-code which is imprinted on each badge. Readers are installed at three entrances to the facility; all other doors are locked. To obtain entry, the employee or visitor passes his or her badge through a bar-code slot reader. Software on a dedicated personal computer categorizes the bar-code, and if the day and time of day are authorized for badges of the determined category, unlocks the associated door for a several-second interval. The system has proved to be reliable and has allowed greater flexibility in the convenient admission of visitors and guests than would have been possible with the conventional, centrally controlled magnetic badge reader used at other facilities.

1. Human Resources Division, ORNL.

2. Instrumentation and Controls Division, ORNL.

1989 SYMPOSIUM OF NORTHEASTERN ACCELERATOR PERSONNEL

R. C. Juras *N. L. Jones*
G. D. Alton *S. N. Lane*
D. L. Haynes *M. J. Meigs*¹
C. M. Jones *G. D. Mills*
*N. F. Ziegler*²

The 1989 Symposium of Northeastern Accelerator Personnel (SNEAP '89) was held in Oak Ridge during the period October 23-26, 1989. In this twenty-third symposium of the series, 97 participants from 11 countries met to discuss the technology and development of electrostatic accelerators and associated boosters.

Proceedings of the symposium, including transcripts of discussions, were published in 1990 and are available from World Scientific Publishing Co., Ltd.

The symposium was hosted and the proceedings were primarily edited by Holifield Facility staff members.

-
1. Instrumentation and Controls Division, ORNL.
 2. Consultant.

FACILITY OPERATIONS AND DEVELOPMENT

HHIRF EXPERIMENTS

R. L. Robinson

Experiments performed at the Holifield Facility in FY 1990 are listed in Table 1.5. Some of these 46 experiments were performed in more than one part, giving a total of 56 runs. Experiments with a prefix of H were those recommended by PAC; those with a prefix of D were discretionary.

The number of research hours (4093) is down from that achieved in FY 1989 (4829 hours) because of budgetary constraints. It was necessary to reduce the number of 8-hour research shifts from 21 per week to an average of 15 1/2. These were arranged to have 31 consecutive shifts in a two-week period. Another consequence of the tight budget was that it was not possible to run coupled experiments in the latter third of the year. Thus, the percentage decrease in coupled hours was larger than that for the tandem (677 coupled hours in FY 1990 versus 1110 hours in FY 1989).

Table 1.6 shows the distribution according to the general area of physics; the distribution according to target station is given in Table 1.7. Spokesmen from outside ORNL represented experiments utilizing 67% of the total research hours.

EXPERIMENTAL APPARATUS

<i>R. L. Auble</i>	<i>R. W. Miles</i>
<i>C. Baktash</i>	<i>C. A. Reed</i>
<i>J. W. Johnson</i>	<i>R. L. Robinson</i>
<i>I. Y. Lee</i>	<i>D. Shupira</i>
<i>M. E. Whitley</i>	

The major development efforts have been on the Recoil Mass Spectrometer and Gammasphere. Due to significant budgetary constraints, very few changes to the existing apparatus, including the electronics pool, could be undertaken. One significant development was the expansion of the Ge-detector recovery system

to allow simultaneous annealing of up to six detectors. This has proven to be essential in view of the heavy usage of these detectors during the past year. A total of 43 detector recoveries were attempted using this system. Only six of these detectors could not be recovered and had to be returned to the vendor. A cryopump was placed on the recovery system to provide better vacuum than was possible with the sorption pumps used previously. This allows the detectors to be maintained at high vacuum ($< 10^{-5}$ Torr) during the annealing process. The annealing temperature has also been reduced slightly, which appears to have improved the success rate, possibly due to reduced outgassing of volatile components inside the detector housing.

HILI Detector System

A Time-of-Flight arm for use in conjunction with the HILI was installed, tested, and used in a scheduled experiment. This facility, supported in part by and in cooperation with the University of Maryland, provides all of the capabilities of the original TOF facility plus the additional power of the HILI detectors.

A ring of 16 charged-particle telescopes, each consisting of a thin organic scintillator affixed to a much thicker CsI crystal, has been developed and built by C. F. Maguire's group from Vanderbilt University. This has been installed in the HILI to extend the angular range from 20 to 27 degrees. Maguire has recently received funding to build an additional five rings, of 16 telescopes each, that will increase the angular coverage of HILI to near 4π .

Spin Spectrometer

A new scattering chamber, similar in design to the original spherical chamber for the Spin Spectrometer, but with a smaller diameter, has been completed. The smaller size provides the clearance needed to install collimators on the anti-Compton shields when Ge-detectors are used in the Spin Spectrometer.

Table 1.5. Experiments completed at the HHIRF October 1, 1989 to September 30, 1990.

Title	Spokesman	Run No.	Target Station	Beam		Research Hours
				Type	E(MeV)	
Tandem						
Decay of Mass-Separated ^{137}Eu	Braga (Georgia Tech)	H217	UNISOR	^{40}Ti	250	24
Shape Coexistence in Odd-Mass Neighbors of Even-Even Nuclei with Low-Lying 0^+ States: On-Line Nuclear Orientation of ^{200}Hg and ^{202}Hg in Fe	Zganjar (Louisiana SU)	H240	UNISOR-NOF	^{16}O	125,140	104
Nuclear Orientation of ^{180}Au	Kraus (Oregon SU)	H250	UNISOR-NOF	^{13}C	140	24
Fusion Cross Sections in the Sub-barrier Region for $^{36}\text{Ar} + ^{90}\text{Zr}$	Sackton (ORNL)	H259	Velocity Filter	^{36}Ar ^{90}Zr	211-250 211-260	107
Continued Search for Hyperdeformed Nuclei	Sarantites (Washington U)	H264	Spin Spectrometer + Ge	^{24}Mg ^1H	110 12	172
Shape Coexistence and Electric Monopole Transitions in ^{192}Pt	Wood (Georgia Tech)	H266	UNISOR	^{16}O	176	93
Shape Evolution Studies in Neutron-Rich $^{148,150}\text{Rh}$	Dejbnksh (Texas A&M U)	H267	Spin Spectrometer + Ge	^{11}B	66	104
Alpha Decay Studies of Light Au and Ir Nuclei	Bingham (U Tennessee)	H270	UNISOR	^{16}O ^{13}C	176 155	104
Radiative Relaxation in Resonant Coherent Excitation of Channeled Ions	Datz (ORNL)	H271	Atomic-43	^{24}Mg	130,175	96
Direct Excitation and Resonant Coherent Excitation of Channeled Ions	Datz (ORNL)	H272	Atomic-43	^{40}Ti	250-350	81
Search for Superdeformed Bands in Odd-Odd Nuclei	McHarris (Michigan SU)	H274	CSS (Compact Ge Ball)	^{35}Cl	145-160	75
Tests of New Collective Modes Predicted by Fermion Dynamical Symmetry Models in A = 130 Region	Hamilton (Vanderbilt U)	H276	CSS (Compact Ge Ball)	^{36}S	159,167,175	128
Nuclear Orientation of ^{180}Au and ^{182}Pt	Kraus (Oregon SU)	H283	UNISOR	^{13}C	120,140	141
EPACT Flight Calibration	Reames (NASA/GSFC)	H284	1.6-m Chamber	^{197}Au ^{56}Fe	550 400	37
Lifetime Measurements in ^{140}Lu	Yu (U Tennessee)	H288	CSS (Compact Ge Ball)	^{44}Sc	205	220
Empirical Estimates of Proton-Neutron Residual Interactions in ^{86}Rb	McNeill (ORNL)	H289	UNISOR	^{28}Si	120	53

Table I.S. (Continued)

Title	Sponsor	Run No.	Target Station	Beam		Research Hours
				Type	E(MeV)	
Search for Characterization of a Low-Spin Superdeformed State in ^{199}Hg via the Decay of the ^{199}Tl 2-Isomer	Henry (LLNL)	H290	UNISOR	^{16}O	125	96
Entrance Channel Effect in Orbiting Reaction	Ray (ORNL)	H291	Split-Pole Magnet	^{32}P	70,136,146	121
Subbarrier Many-Nucleon Transfer Reactions	Kim (ORNL)	H295	Split-Pole Magnet	^{19}Ne	292,308	45
Search for Superdeformation at Low Spin in ^{199}Hg	Zganjar (Louisiana SU)	H297	UNISOR	^{16}O	115,176	97
Search for Superdeformation in ^{199}Tl	Riedinger (U Tennessee)	H298	Spin Spectrometer + GE	^{36}S	160,165,170	143
E0 Transition Intensities in $^{134,136}\text{Te}$, and ^{134}Sn	Walters (U Maryland)	H299	UNISOR	^{32}S	220	90
Test of Shape Coexistence in Ge-Se Nuclei and a Search for Mixed-Symmetry States	Hamilton (Vanderbilt U)	H301	UNISOR	^{16}O	50,55,60	118
High Resolution Measurements of X-rays from Dielectronically Excited Ions in Crystals	Vane (ORNL)	H302	Atomic-35	^{40}Ca	170,205,220	70
Radiative Electron Capture in Channeled Heavy Ions	Vane (ORNL)	H303	Atomic-35	^{32}S ^{48}Ti	120,160,199 250,300,325	60
Pre-equilibrium Proton Emission	Teichmann (U Rochester)	H304	Velocity Filter	^{28}Si ^1H	65,254 25	117
Measurement of Magnetic Moments of Odd-Odd ^{149}In , ^{149}I and ^{149}I	Walters (U Maryland)	H305	UNISOR-NOF	^{32}S	185	70
On-Line Nuclear Orientation Measurements of Quadrupole Moment Ratios in Iodine Isotopes: Shape Coexistence in $^{135,137}\text{I}$	Stone (Oxford U)	H307	UNISOR-NOF	^{32}S	165	34
The α Reduced Widths of ^{199}Pb or ^{199}Pb	Toth (ORNL)	H308	Velocity Filter	^{58}Ni ^{48}Ti ^{76}Se	275 220 340	86
Search for O+ Superdeformed States in ^{199}Hg and ^{199}Pb	Akmal (ORNL)	H310	UNISOR	^{16}O	176,195	34
Search for Superdeformation in ^{209}Po or ^{199}Tl	Piotte (U Tennessee)	H317	Spin Spectrometer + Ge	^{24}Mg	127-133	175
Search for a Negatively-Decoupled Superdeformed Band	Garrett (ORNL)	H319	Spin Spectrometer + Ge	^{27}Al	140,145	174

Table 1.5. (Continued)

Title	Spokesman	Run No.	Target Station	Beam		Research Hours
				Type	E(MeV)	
Development of Time-of-Flight System on HILL	Mignerey (U Maryland)	D047	HILL	^{58}Ni	340	27
HILL Detector Development	Shapira (ORNL)	D047	HILL	^{16}O	80	18
Charge State Distributions of ^{58}Ni Ions Emerging from Thin Carbon Foils	Martin (ORNL)	D058	Beam Line 17	^{58}Ni	180-300	21
Test of a New Detector System for use with the Velocity Filter	Toth (ORNL)	D060	Velocity Filter	^{48}Ti	220	12
UNISOR Ion Source Development	Carter (ORAU)	D064	UNISOR	^{13}C ^{28}Si ^{16}O ^{32}S ^{35}Cl ^{48}Ti	115 126 176 160,200,250 180 215,225,250	66
Search for Low-Spin Superdeformed States in ^{199}Hg	Akovioli (ORNL)	D076	UNISOR	^{16}O	176	19
Search for Highly Aligned Multi-quasi Particle Configurations in Doubly Odd Nuclei	Kreimer (Tandem-CNEA Argentina)	D079	Spin Spectrometer + Ge	^{16}O	99,101	146
Elastic Scattering of ^{16}O (75 MeV) on $^{72,74}\text{Ge}$	Gross (ORNL)	D080	1.6-m Chamber	^{16}O	75	14
Coupled						
Measurements on Mn/Mp in ^{208}Pb and ^{164}Ce	Horen (ORNL)	H242	Broad-Range Magnet	^{17}O	375	209
Nucleon Transfer and Excitation Energy Division in the Reaction ^{44}Ca on ^{209}Bi at 15 MeV/u	Mignerey (U Maryland)	H277	HILL	^{44}Ca	600	146
A Systematic Study of Giant Dipole Resonance Excitation by Inelastic Heavy-Ion Scattering	Reene (ORNL)	H281	Broad-Range Magnet	^{17}O	375	129
Octupole Deformation of ^{140}Nd and ^{150}Sm	Cline (U Rochester)	H286	Spin Spectrometer + Ge	^{140}Nd ^{150}Sm	701 701	156
Sharing of Excitation Energy in Complex Fragment Emission of $^{79}\text{Br}+^{27}\text{Al}$ at 12 MeV/A	Wieleczko (Saclay, France)	H300	HILL	^{79}Br	930	26
Coulomb Excitation of ^{159}Tb	Lee (ORNL)	D077	Spin Spectrometer + Ge	^{208}Pb	981	11

Table 1.6. Division of research hours
by research activities for the period
October 1, 1989 through September 30, 1990

Activity	Research Hours (No. of Runs)		
	Tandem	Coupled	Total
High-spin states	992(7)		992(7)
Superdeformation	572(6)		572(6)
Low-level properties	874(12)		874(12)
Alpha decay rate	86(1)		86(1)
Reaction mechanisms	346(3)	172(2)	518(5)
Giant resonances		338(3)	338(3)
Quasi-elastic	59(2)	167(2)	226(4)
Atomic	327(6)		327(6)
Test of detectors	49(2)		49(2)
Test of apparatus	111(10)		111(10)
Total	3,416(49)	677(7)	4,093(56)

Table 1.7. Use of experiment target stations for the period October 1, 1989 through September 30, 1990

Target Station	Beam Line	Research Hours (No. of Runs)		
		Tandem	Coupled	Total
UNISOR	C16B	1167(23)	0	1167(23)
Spin Spectrometer	C15	765(6)	167(2)	932(8)
Close-Packed Ge Ball	23	571(4)	na	571(5)
Broad-Range Magnet	C18	0	338(3)	338(2)
Velocity Filter	21	323(4)	na	323(4)
HILI	51A/C17	46(2)	172(2)	218(4)
Atomic-35	35	183(3)	na	183(3)
Split-Pole Magnet	33	166(2)	na	166(2)
Atomic-43	43	123(2)	na	123(2)
1.6-m Scattering Chamber	C16A	51(2)	0	51(2)
Beam Line 17	17	21(1)	na	21(1)
Total		3,416(49)	677(7)	4,093(56)

na = not accessible to beam

Recoil Mass Spectrometer

The ORNL Recoil Mass Spectrometer, which was designed by J. D. Cole (INEL), Tom Cormier (Texas A&M University) and J. H. Hamilton (Vanderbilt University), is a new generation device for detection of reaction products. The Technical Specifications required for the request of bids was completed in June. Bid packages were received in September and are now undergoing technical reviews and cost analysis.

Gammasphere

The Gammasphere, which is a 4π array of 110 Compton-suppressed Ge detectors, is a major initiative of the nuclear structure community. It will have the capability to observe up to fivefold coincident events and through this provide a resolving power of 1000 times higher than that achieved from twofold events, as are normally used today. This device will be funded \$17M over 3 years with \$5.5M budgeted for it in FY 1991. The Holifield was recommended as the Gammasphere site by a DOE appointed Gammasphere Siting Panel which met in June 1988.

During the past year the Physics Division staff has made a major contribution in the development of this device. The integral of this has amounted to about 4.2 work years of effort. This strong effort was made in order to have the project progress rapidly enough to be prepared to use the capital funds as they are made available in early FY 1991. Activities of the staff have included design of the spherical support system, development of computer software/hardware, performance of detector simulation calculations, and design studies of the inner BaF_2 ball and of the liquid nitrogen system. Details of these activities can be found in the Experimental Nuclear Physics section of this report.

Gammahall

Since the Holifield was recommended as the site for Gammasphere, the Holifield staff has developed a conceptual design for a new target room to house both the Gammasphere and the RMS. This room (the Gammahall), which is shown in Fig. 1.8, is approximately 100 ft X 40 ft. It is designed to accommodate the Gammasphere in the stand-alone position or in conjunction with the RMS at either the target or focal plane position. Two bending magnets (one in room C114 and one on the beam line just prior to room C114), will raise the beam line from its normal height of 4 ft to 8 ft as required by the large size of the Gammasphere. Since it is impractical to swing the RMS because of its size (about 70 ft long), the angle for study of ejectiles relative to the beam direction will be changed by a beam swinger placed before the RMS. A counting room for both the RMS and Gammasphere will be located in the existing "south addition" of the Holifield facility. Adjoining that space will be a detector laboratory in part to provide an area where Ge detectors can be annealed.

The conceptual design and pre-engineering work for Gammahall is completed. ORNL has obligated \$1.2M for construction of Gammahall.

COMPUTER SYSTEMS

<i>W. T. Milner</i>	<i>J. W. McConnell</i>
<i>J. R. Beene</i>	<i>S. Pilotte</i>
<i>J. A. Biggerstaff</i>	<i>C. N. Thomas²</i>
<i>R. L. Varner</i>	

VAXCluster and Network Development

R. L. Varner and C. N. Thomas

The VAXCluster has been expanded significantly this year to include the MicroVAX's associated with the WA80 project. This addition was designed to reduce the management burdens and provide easy access to batch and print queues on the

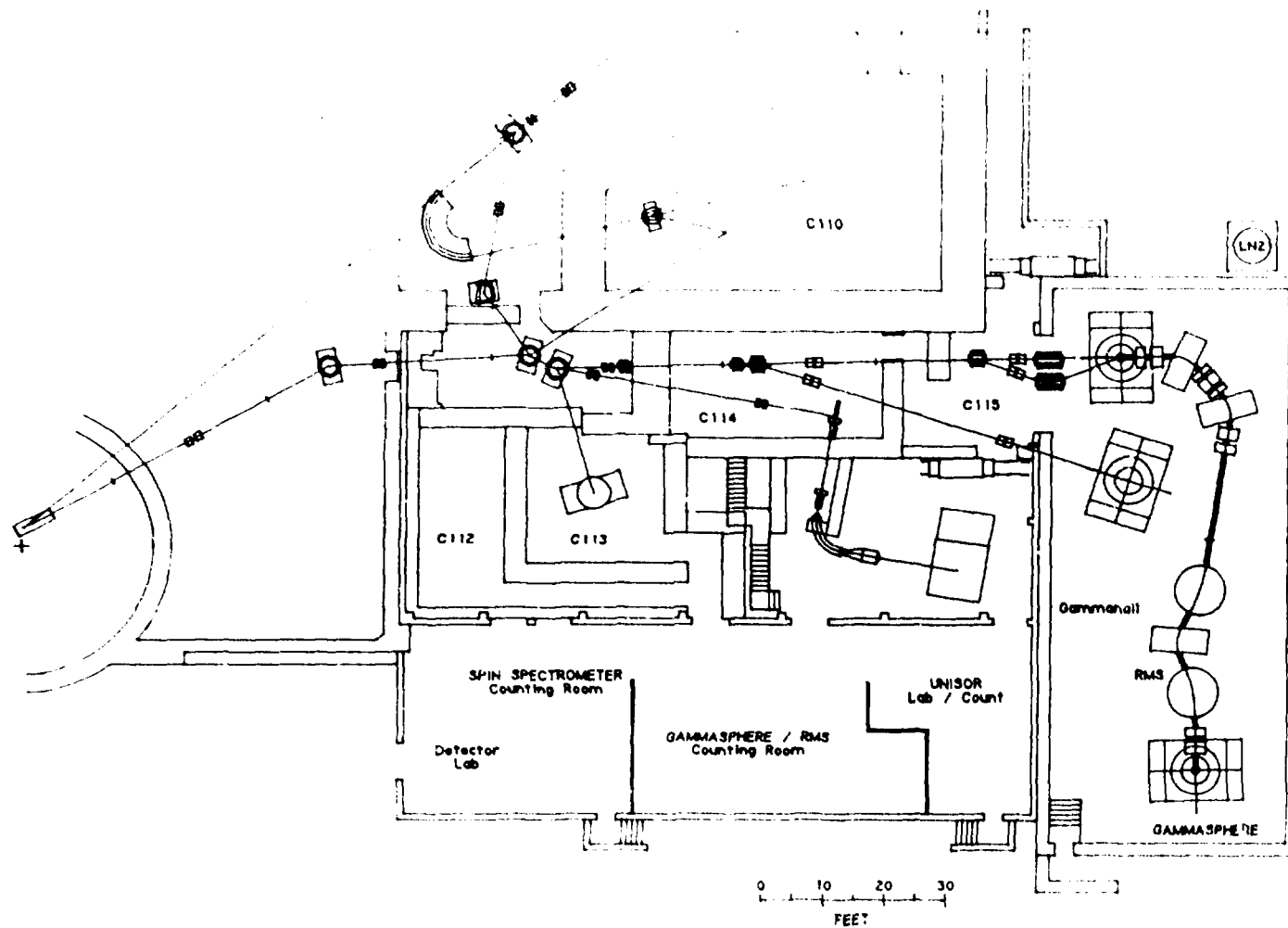


Fig. 1.8. Planned addition to house the Gammasphere and RMS is shown here on the east side of the existing building.

main VAX's. There have been some minor hardware additions, including adding an extra Exabyte tape drive to the VAXCluster central nodes and another Postscript laser printer. The local Ethernet has been extended to the Joint Institute, where it is being used to support workstations, and we have added 16 additional terminal lines to provide better computer access for Joint Institute visitors.

There have been several major software upgrades, enhancing significantly the connectivity of the Physics Division with the outside world. The first software upgrade was to add Multinet TCP/IP to the central nodes of the VAXCluster, providing our users with TELNET and FTP access to remote nodes on the Internet, as well as to the growing body of UNIX computers at the laboratory and in the Physics Division. The cluster also serves its disks to selected nodes in the Physics Division and to the INTEL Hypercube using the NFS disk service software provided by the Multinet package. The Internet service has been valuable in communicating with various supercomputer centers in the U.S., as well as providing better connections to the large number of university users who have only Internet connections. The NFS service has been quite valuable to several groups in the Physics Division, enabling them to use Physics disk space while developing programs on the Hypercube in the Mathematics and Statistics Research Division. The Hypercube is quite disk poor, so this enabled early research in parallel computing to proceed. The NFS service will prove valuable later when the ORNL's Computing and Telecommunications Division begins serving the laboratory Mass Store to the NFS network, providing us with very large amounts of inexpensive storage.

The Physics VAXCluster also joined the BITNET this year, becoming node ORPH01 ("zero one"). This improves our connections to BITNET considerably, since we had previously relied on nodes in ORNL managed by other divisions to provide us with these services. It is now much easier for short term visitors to HHIRF to receive and send BITNET messages.

Parallel Processor Development

J. W. McConnell

A VME-based parallel processor system for data acquisition has been implemented. This system accepts a raw data stream from the Event Handler and allows real-time modification or rejection of event data prior to sending a data stream to the Concurrent system for recording on tape and histogramming. User programs, written in FORTRAN or C, process the event-by-event data in real-time. The system was first used for a HHIRF experiment in June. Since that time, it has been used on all Compton Suppression experiments where real-time gain-matching provides better experiment monitoring and, in some cases, eliminates one tape scan.

A MicroVAX II computer is interfaced to the VME system and serves as a host for the parallel processor software development. Currently we use a VME processor based on a 16-Mhz 68020 with a 68882 floating point coprocessor. This processor module was developed at Fermilab and is commercially available from Omnibyte. The system can have up to 15 VME processor modules providing approximately 25 VUPs of processing power for the system. An additional processor serves as the system master controller which manages the input and output data streams. The input data stream is interfaced to the VME system using an Ikon DR11W emulator and a custom controller which detects end-of-event flags in the input stream. A second DR11W emulator interfaces the VME system output data stream to existing Concurrent BMF interfaces. The input rate is limited to approximately 1.85 Mbytes/sec and the output rate is limited to 780 Kbytes/sec.

Two software development systems are available: (1) the ACP system developed at Fermilab and based on an Absoft FORTRAN compiler and (2) a system based on Green Hills Software C and FORTRAN compilers. The Green Hills FORTRAN compiler provides nearly a two times improvement in processing speed over the ACP Absoft system.

Data Reduction on RISC/UNIX Workstations

J. R. Beene

Data reduction is a persistent crisis in heavy-ion nuclear physics. As our experiments and the information we attempt to extract from them become more and more complex, we have gradually lost the ability to reduce the data to a form suitable for interpretation and publication in a reasonable time. On our standard data reduction computers (Concurrent 3230 MPS) the complex primary processing of event tapes from our most elaborate experiments now requires on the order of 10 hours per 100 Mbytes of raw data, with subsequent secondary passes taking 15 to 30 minutes per 100 Mbytes. A typical experiment might acquire 30,000 Mbytes (30 Gbytes) of data. If one realizes that this is computer time alone, not counting time for software development, testing, generation of calibration and gating data, etc., etc., it is easy to see why the time required to complete processing of complex experiments is so long.

There are a number of possible answers to this data reduction crisis. Very fast processing engines are commercially available, but they are currently beyond our financial resources. One of the most promising and potentially cost-effective directions, which is being vigorously pursued at ORNL, is the multiprocessor "CPU farm" concept, pioneered by Fermilab. While these "farms" are being employed effectively on the very large data sets produced in high-energy physics or relativistic heavy ion physics, they are still difficult and cumbersome to use in low- and medium-energy nuclear physics for routine data reduction. However, the recent dramatic increase in performance, and decrease in price of RISC cpu based computers has provided us with immediate relief which will buy us time to learn to use the farms of the future effectively. Commercial RISC based workstations, running the UNIX operating systems can be configured in a form suitable for data

reduction (at least 24 Mbytes of memory, 900 Mbytes of disk, two 8-mm cassette tape drives, high resolution color monitor) for under \$40,000. We have modified and adapted a significant subset of the standard HHIRF data reduction software to run on such a machine (a DECstation 3100, running ULTRIX). Most of the work of the adaptation involved doing efficient disk and tape I/O overlapped with processing. Exabyte tape I/O required special attention, since a driver optimized for use with this device was not yet commercially available. The DECstation 3100's MIPS R2000 CPU is nominally rated at about 10 to 15 times faster than the Concurrent 3230. For a typical test case, analysis ran about 12 times faster on the DECstation 3100, indicating that we are able to realize the full gain expected on the basis of nominal CPU speeds.

All software needed for routine tape scanning work are available and have been extensively tested during the analysis of two complete experimental data sets.

Because excellent network access to other ORNL computer facilities are available from the DECstation, adaptation of secondary data reduction (mostly interactive graphics programs) was treated as a slightly lower priority. Work on adapting these programs is now well under way. We expect to have essentially the whole standard suite of ORNL/HHIRF data reduction programs (including graphics, using X-windows) adapted to run efficiently under UNIX in a very short time.

As noted in the next subsection, the RISC/UNIX hardware chosen for initial general use of this software at HHIRF is the DECstation 5000, which is a factor of about 1.6 times faster than the DECstation 3100 discussed above, and has a data reduction throughput equivalent to that of a CPU farm consisting of approximately nine Motorola 68020 (16 MHz) processors.

New Data Acquisition and Processing Equipment

R. L. Varner and C. N. Thomas¹

Three DECstation 5000 workstations (each with 24 MByte of memory, 600 MByte of disk storage and two Exabyte tape drives) were procured as part of the general program to upgrade the data processing capacity of the facility. At the time of this writing, two systems have been delivered but not yet made available for use and the third is soon to be delivered. These machines (each with a rated and demonstrated performance of 24 MIPS) are expected to become the primary resource for off-line data processing during the coming year.

Six additional 8-mm Exabyte tape drives have been procured for the Concurrent system, increasing the total from two to four per system. Almost all data acquisition and processing is now done using the Exabyte system. A 1.2-GByte disk drive was added to CPU-B to replace older 300-MByte drives which had failed to provide sufficient increased storage.

Graphics and Analysis Development

W. T. Milner

Data manipulation and display program DAM and spectrum analysis program SAM (previously implemented on Tektronix 4100 and 4200 series terminals and VAXstations running UIS windows) have been combined into one package (DAMM) and adapted for use on VAXstations running VMS and DECwindows. Two-dimensional manipulation program TDX was also incorporated into the package. Documentation and HELP facilities have been revised. This adaptation was made using the Fortran calls (binding) to routines in the Xlib library. In the near future, a C binding adaptation will be implemented so that DAMM can be used on DECstations and possibly other UNIX based workstations.

1. Oak Ridge Associated Universities.

USERS GROUP ACTIVITIES

R. L. Auble

During the past year, the Executive Committee met with the Scientific Director on four occasions to provide guidance on the operation of the facility, recommendations on capital equipment expenditures, and to recommend prospective members of the Program Advisory Committee. The Committee also provided valuable input on the preparations for the NSAC Heavy-Ion Facility review. Members of the Executive Committee are listed in Table 1.8.

Table 1.8. Users Group Executive Committee

1989

Doug Cline¹, University of Rochester
 Carroll Bingham², University of Tennessee
 Joe Hamilton, Vanderbilt University
 Ken Toth, Oak Ridge National Laboratory
 Richard Schmitt, Texas A&M University
 John Wells, Tennessee Technological University

1990

Carroll Bingham¹, University of Tennessee
 Demetrios Sarantites², Washington University
 Ken Toth, Oak Ridge National Laboratory
 John Rasmussen, Lawrence Berkeley Laboratory
 Richard Schmitt, Texas A&M University
 John Wells, Tennessee Technological University

¹Chairperson

²Chairperson elect

The annual meeting of the HHIRF Users Group was held on October 13, 1989 at the Asilomar Conference Center in conjunction with the APS/DNP meeting. Progress and status reports were presented on facility operations and experimental apparatus.

with an emphasis on the recently commissioned nuclear orientation facility, the Recoil Mass Spectrometer, and Gammasphere.

A nominating committee, charged with selecting four candidates for election to the Executive Committee, was chaired by Cyrus Baktash. The other members of the committee were: D. Cline (University of Rochester), J. Wood (Georgia Tech), L. Sobotka (Washington University), and J. Cole (INEL).

THE HHIRF PROGRAM ADVISORY COMMITTEE

R. L. Robinson

The Holifield PAC, which is composed of 6 to 7 senior scientists from throughout the community, has the responsibility of evaluating the scientific merit of proposed experiments and recommending which should be approved time as based primarily on the physics. The HHIRF PAC has continued its pattern of meeting every 6 months as it has since the Holifield Facility began routine operation in 1984. Statistics on the two PACs which met in FY 1990 and the one planned for November 1990 are included in Table 1.9.

There has been a significant increase in hours requested through proposals submitted to PAC during the past two years as can be seen in Fig. 1.9. This has occurred at a time when budgetary constraints have reduced the number of available hours. As a result, PAC has not been able to recommend hours for many good experiments.

The members of PAC 14-16 are given in Table 1.10. Other nonparticipating attendees of one or both of the FY 1990 meetings were the chairman of the Executive Committee of the Users Group (D. Cline in 1989, C. Bingham in 1990), the HHIRF Users Liaison Officer (R. L. Auble), and the Physics Division Director (J. B. Ball). The meetings were chaired by R. L. Robinson.

THE JOINT INSTITUTE FOR HEAVY ION RESEARCH

R. L. Robinson J. H. Hamilton¹

L. L. Riedinger²

The Joint Institute for Heavy Ion Research is a collaborative endeavor of the University of Tennessee, Vanderbilt University, and Oak Ridge National Laboratory. It is administered by the University of Tennessee through the Science Alliance which is one of the State of Tennessee's Centers of Excellence. Two-thirds of the funding of the Joint Institute is provided by the Science Alliance; the remainder is provided by Vanderbilt University, DOE, and ORNL. The Joint Institute is housed in two buildings which adjoin the Holifield Facility.

The purpose of the Joint Institute is to enhance and stimulate the scientific environment of the Holifield Facility to the mutual benefit of its sponsoring institutes. This is accomplished through three activities: (1) a guest program, (2) sponsorship of meetings held at the Joint Institute, and (3) operation of a dormitory facility for users of the Holifield Facility.

Table 1.11 lists guest during FY 1990 who were supported, in part or fully, by the JIHIR. The average length of appointment in FY 1990 for the 69 guests was near three months.

The Joint Institute sponsored the four meetings noted in Table 1.12. The Theory Users Group Meeting, the sixth annual meeting in this series, was attended by over forty nuclear theorists primarily from southeastern universities, for the purpose of informally discussing a variety of topics in nuclear theory. The Gammasphere meeting concentrated on finding the best design for detectors of that device. The emphasis of the Conference on Nuclear Structure in the Nineties (which, because of the large number of attendees could not be held at the Joint Institute) was on recent developments in several areas involving high spin and temperature behavior in nuclei (e.g.,

superdeformation, static and dynamic pairing, properties of rapidly rotating nuclei). The purpose of the Second UNISOR Nuclear Orientation Workshop was to discuss analysis techniques and problems encountered with existing data and future "fridge" experiments.

The dormitory accommodated 338 users of the Holifield Facility during FY 1990. The average length of each visit was over six nights for a total of 2124 person-nights.

A specific project of the Joint Institute has been to develop and to serve as the focus of a nuclear structure theory center. Such a center will fill a void in the U.S. and will complement the strong experimental programs at the Holifield. This will become even more important as the Gammasphere and RMS are brought into operation in about two years. The Joint Institute already has made significant progress in the creation of this center.

A key element of it is the theory position within UNISOR that was filled this past August by Ragnar Bengtsson. The Joint Institute is providing full funding for a postdoctoral position which was recently filled by Ramon Wyss. Witez Nazarewicz will begin, this coming January, a two-year guest appointment with the Joint Institute. These efforts are natural extensions of the support that the Joint Institute has been providing in this area since 1984. For example, during FY 1990, it supported 22 nuclear structure theorists for a total time of two person-years. In addition, the Joint Institute has supported, annually, a theory month and a theory workshop.

-
1. Vanderbilt University.
 2. University of Tennessee.

Table 1.9. Information on PAC-14, PAC-15, and PAC-16

	Meeting Date	Hours Requested	Hours Recommended	Rec/Req.
PAC-14	Oct. 30, 1989	3888	2128	55%
PAC-15	May 10, 1990	2928	1696	58%
PAC-16	Nov. 2-3, 1990	4208	~1750	42%

Table 1.10. Members of PAC-14, PAC-15,
and PAC-16

Member	Institute	PAC
R. Betts	ANL	14
R. Bengtsson	ORAU	16
C. L. Cocke	Kansas State University	14,16
R. M. Diamond	LBL	14,15
J. P. Draayer	Louisiana State University	15,16
D. H. Feng	Drexel University	14
S. Landowne	ANL	15,16
C. J. Lister	Yale University	15,16
W. G. Lynch	Michigan State University	15,16
J. B. Natowitz	Texas A&M University	14
P. H. Stelson	ORNL	14-16

HHIRF PACs

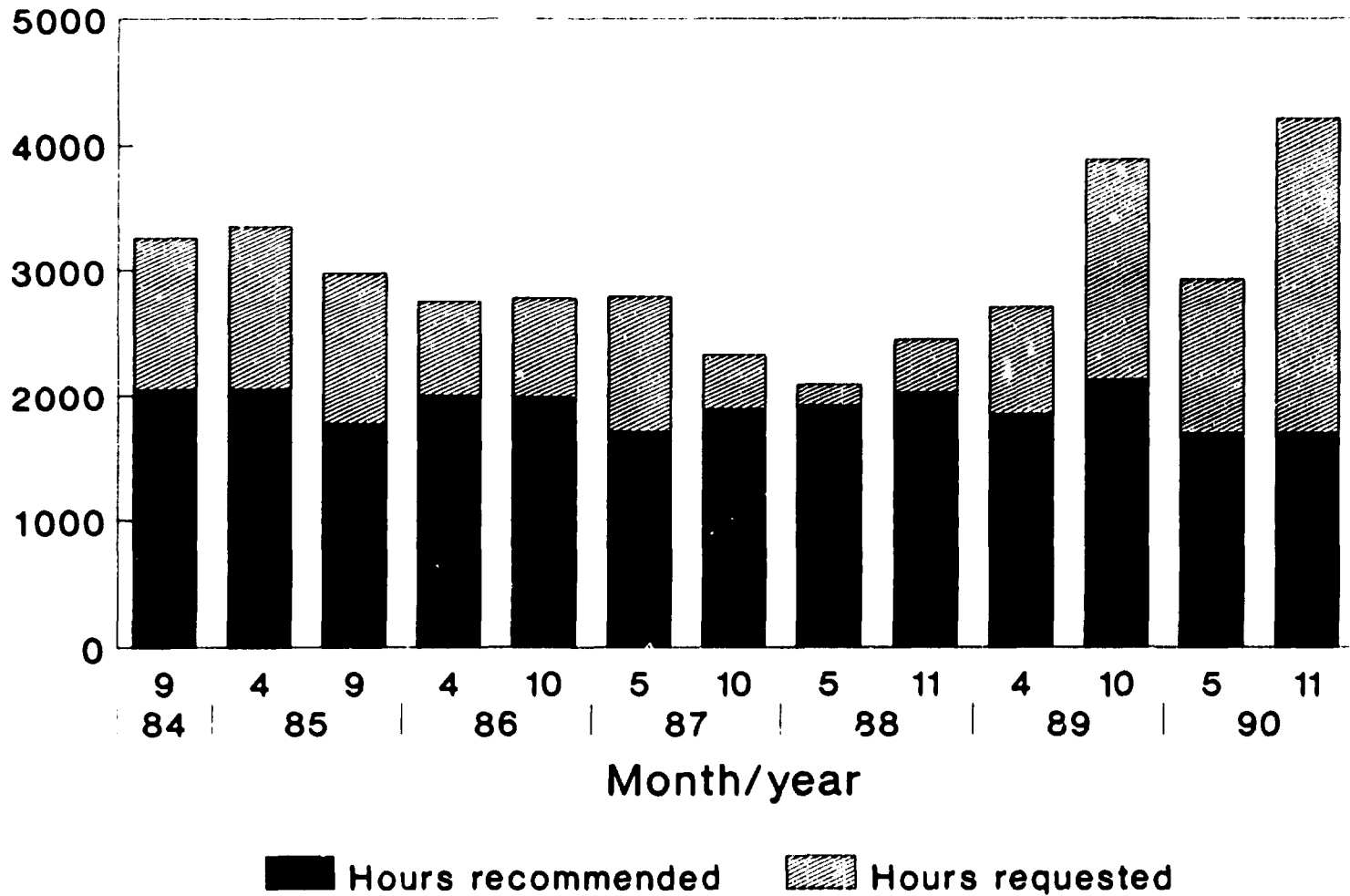


Fig. 1.9. Research hours requested in proposals submitted to PAC since September 1984 as indicated by the total bar. The solid portion of the bars indicate the portion that was recommended.

Table 1.11. Guest scientists at the Joint Institute for Heavy Ion Research during the period of October 1989 - September 1990

Name	Institute	Length of Appointment
B. Andersson	SUNY	3 days
W. Andrejtscheff	Inst. Nuclear Research (Bulgaria)	1 week
A. Balantekin	Univ. of Wisconsin	2 days
M. Baranger	MIT	3 days
R. Bengtsson	Univ. of Lund (Sweden)	2 weeks
K. Bhatt	Univ. of Mississippi	2 weeks
P. Butler	Univ. of Liverpool (United Kingdom)	2 months
L. Chaturvedi	Vanderbilt Univ.	1 week
E. Chavez-Lomeli	National Univ. of Mexico (Mexico)	1 year
Y. Chen	Inst. Atomic Energy (China)	4 weeks
F. Donau	Inst. Nuclear Research (Germany)	4 weeks
J. Draayer	Louisiana State Univ.	5 days
J. Dudek	Centre de Recherches Nucleaires (France)	1 month
D. Ernst	Texas A&M Univ.	1 month
S. Frauendorf	Neils Bohr Inst. (Denmark)	2 weeks
N. Glendenning	Lawrence Berkeley Lab.	2 days
W. Greiner	Univ. of Frankfurt (Germany)	6 weeks
D. Hamilton	Univ. of Sussex (England)	6 months
W. Haxton	Univ. of Washington	2 days
B. Herskind	Neils Bohr Inst. (Denmark)	3 weeks
K. Heyde	Univ. of Gent (Belgium)	2 weeks
N. Isgur	Univ. of Toronto (Canada)	2 days
R. Kirchner	GSI (Germany)	6 weeks
M. Kirson	Weizmann Inst. Science (Israel)	1 month
M. Korolija	Ruder Boskovic Inst. (Yugoslavia)	4 months
A. Kreiner	CNEA (Argentina)	6 weeks
S. Kumano	Indiana Univ.	2 days
K. Liu	Univ. of Kentucky	2 days
Y. Liu	Univ. of Tennessee	10 months
W. Ma	Tsinghua Univ. (China)	9 months
C. Mahaux	Univ. of Liege (Belgium)	1 month
K. Matsuyanagi	Kyoto Univ. (Japan)	2 weeks
J. McNeill	ORNL/JHIR	10 months
B. Mottelson	Neils Bohr Inst. (Denmark)	2 weeks
B. Mueller	Univ. of Frankfurt (Germany)	4 days
J. Mueller	Univ. of Frankfurt (Germany)	1 year

Table 1.11. (Continued)

Name	Institute	Length of Appointment
M. Nagarajan	Daresburg Laboratory (England)	10 days
W. Nazarewicz	Warsaw Technical Univ. (Poland)	4 days
N. Neskovic	Boris Kidric Inst. (Yugoslavia)	11 days
V. Oberacker	Vanderbilt Univ.	2 days
V. Pashkevich	JINR (USSR)	8 days
R. Pisarski	Brookhaven National Lab.	5 days
S. Pratt	Univ. of Wisconsin	5 days
I. Ragnarsson	Univ. of Lund (Sweden)	6 days
A. Ray	ORNL/JIHIR	1 year
E. Remler	William & Mary College	2 days
J. Robertson	Univ. of Kentucky	4 weeks
N. Rowley	Daresbury Lab. (England)	12 days
S. Saini	ORNL/JIHIR	1 year
Y. Shimizu	Kyushu Univ. (Japan)	2 weeks
P. Semmes	Tennessee Technological Univ.	8 weeks
H. Sorge	Inst. Theoretical Physics (Germany)	2 days
W-G. Spang	KFA, Julich (Germany)	1 month
I. Stone	Oxford Univ. (United Kingdom)	2 months
N. Stone	Oxford Univ. (United Kingdom)	2 months
J. Stryjewski	GANIL (France)	8 days
E. Suraud	GANIL (France)	1 week
K. Teh	ORNL/JIHIR	10 days
M. Thoennessen	ORNL/JIHIR	1 year
U. Thumm	Univ. of Freiburg (Germany)	11 months
M. Tincknell	ORNL/JIHIR	1 year
S. Wallace	Univ. of Maryland	2 days
J. Wambach	Univ. of Illinois	5 days
J. Wieleczo	CEN, Saclay (France)	9 months
D. Winchell	Univ. of Pittsburgh	1 year
C. Wu	Jilin Univ. (China)	3 months
R. Wyss	Royal Inst. Tech. (Sweden)	3 months
P. Zeijlmans van Emmichoven	RTU (Netherlands)	1 year
J. Zhang	Lanzhou Inst. (China)	7 months

Table 1.12. Meetings sponsored by the JIHIR during FY 1990

Meeting	Date	Attendance	Organizer
HHIRF Theory Users Group Meeting	March 23-24, 1990	46	J. B. McGrory
Gammasphere Steering Committee for Review of Detector Design	April 22, 1990	12	I. Y. Lee
Conference on "Nuclear Structure in the Nineties"	April 23-27, 1990	208	N. R. Johnson
Second UNISOR Nuclear Orientation Workshop	July 31-Aug. 2, 1990	33	H. K. Carter

2. LOW/MEDIUM ENERGY NUCLEAR PHYSICS

NUCLEAR STRUCTURE STUDIES VIA ELASTIC, INELASTIC, AND CHARGE EXCHANGE REACTIONS

MULTIPHONON GIANT RESONANCE EXCITATIONS WITH INTERMEDIATE ENERGY HEAVY IONS

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There has been a recent revival of interest in the study of multiphonon collective strength in nuclei. This interest has been driven partly by the possibility of exciting multiple giant resonance (GR) phonons via Coulomb excitation with relativistic heavy ion beams.⁵⁻⁷

We have carried out an extensive study^{8,9} of GR excitation and decay in ^{208}Pb and neighboring nuclei, using inelastic scattering 84 MeV/nucleon beams of ^{17}O . This work has demonstrated, among other things, that the isovector giant dipole resonance (IVGDR) is excited very strongly (~ 2 b/sr peak differential cross section), and can be isolated and identified very cleanly by its ground state photon decay. For example, the ground state decay branching ratio is found to be about 1.9% for the IVGDR in ^{208}Pb , about two orders of magnitude larger than the corresponding branch for nearby resonances or the underlying continuum.⁸

While most interest in multiple GR excitation has focused on relativistic (i.e. $E > 1$ GeV/nucleon) heavy-ion beams,^{5,6} the question naturally arises as to whether it is possible to study such excitations at intermediate (i.e., ~ 100 MeV/nucleon) energies, where conventional magnetic spectrometers can be used to advantage for high-resolution spectroscopic studies.

We have recently carried out a series of experiments at the French GANIL facility in an attempt to isolate and identify multiphonon strength by its gamma decay and the variation of excitation cross section with projectile Z . Our initial study is on ^{208}Pb excited by inelastic scattering of ^{17}O (84 MeV/nucleon), ^{36}Ar (95 MeV/nucleon), and ^{86}Kr (60

MeV/nucleon). The inelastically scattered projectiles were detected and identified in the magnetic spectrometer SPEG, and coincident γ rays were detected in 228 BaF_2 crystals arranged in 12 close-packed blocks of 19 crystals. These detectors included 57 crystals from the ORNL BaF_2 array, with the remainder coming from the European TAPS collaboration and from GSI.

Analysis of this data has just begun. We will search for evidence for the two-phonon GDR (i.e., $\text{GDR} \otimes \text{GDR}$) which should be centered at an excitation energy, $E^* \sim 27$ MeV, and for mixed two phonon states corresponding to the GDR coupled to the two strong low-frequency vibrations (3^- 2.6 MeV and 2^+ 4.1 MeV) in ^{208}Pb . We expect to find the $E^* \sim 16$ MeV $\text{GDR} \otimes 3^-$ and $E^* \sim 18$ MeV $\text{GDR} \otimes 2^+$ excited with approximately equal cross section (about 200 mb/sr, peak in the Kr induced reaction) and the $\text{GDR} \otimes \text{GDR}$ state excited about half as strongly. For all three of these multiphonon states the primary means of isolation and identification will be the observation of the strong EI decay back to the corresponding (1^- , 2^+ , or 3^-) one-phonon state. Separation of the strongly overlapping ($\Gamma \sim 4$ MeV) $\text{GDR} \otimes 2^+$ and $\text{GDR} \otimes 3^-$ states will be accomplished by requiring $\gamma\gamma$ coincidences with the subsequent ground state deexcitations of the 2^+ and 3^- states. Further unfolding of the one- and two-phonon contributions can be done by comparing the excitations observed with the various probes, utilizing the stronger projectile Z dependence of two-phonon, compared to one-phonon excitation (Z^4 compared to Z^2 at a given projectile velocity).⁷

1. Partial support provided by Vanderbilt University and Joint Institute for Heavy Ion Physics, ORNL.

2. GANIL, Caen, France.

3. II. Physics Institute, Giessen, Germany.

4. GSI, Darmstadt, Germany

5. P. Braun-Munzinger et al., Proposal 814 submitted to AGS Program Committee, accepted 1985.

6. H. Emling, *Proceedings of Nuclear Structure in the Nineties*, Oak Ridge, Tennessee, April 23-27, 1990, in press.

7. G. Baur and N. Baron, *J. Phys. G* **15**, 1661 (1989).

8. J. R. Beene et al., *Phys. Rev. C* **41**, 920 (1990).

9. J. R. Beene et al., *Phys. Rev. C* **41**, R1332 (1990).

A SYSTEMATIC STUDY OF ISOVECTOR RESONANCE EXCITATION BY INELASTIC NUCLEON AND HEAVY ION SCATTERING

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R. L. Auble, M. L. Halbert, D. J. Horen,
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J. H. Hamilton³

There has been substantial interest recently in the excitation of isovector giant resonances by inelastic scattering of hadronic probes,⁴⁻⁶ but there is almost no systematic experimental data on the subject. This is because the cross section for excitation of isovector giant resonances by the hadronic interaction is generally overwhelmed by the much stronger excitation of isoscalar strength in the same excitation energy region. At sufficiently high bombarding energies (>50 MeV/nucleon) cross sections for isovector resonances comparable to those of isoscalar resonances have been observed,⁷ but they result primarily from Coulomb excitation and do not carry much information about nuclear excitation. In order to study hadronic excitation of isovector strength systematically, a technique is required which can deal with the dominant background of isoscalar cross sections. We have developed a tool which provides the needed sensitivity for study of the isovector giant dipole resonance (IVGDR) in all nuclei^{7,8} and a related technique for the isovector giant quadrupole resonance in nuclei near closed shells.⁹

The IVGDR can be identified in coincidence experiments by detecting gamma decays to the ground

state. This provides an enhancement of ~100 to 1 for the IVGDR relative to isoscalar quadrupole strength and much larger enhancements compared to other multipoles.⁷ We have begun a program of systematic study of IVGDR excitation using this technique. Initial experiments have been done using 22 MeV/nucleon ¹⁶O and ¹⁷O projectiles to excite the GDR in ²⁰⁸Pb. The inelastically scattered oxygen ions were identified and detected with the HHIRF Broad Range Spectrograph, and coincident gamma rays were detected in the ORNL BaF₂ array. Analysis of this data has just begun.

We intend eventually to investigate IVGDR excitation as a function of target and projectile neutron excess at HHIRF using oxygen projectiles and Pb and Zr targets. We hope to carry out similar photon coincidence experiments with inelastic proton scattering from Pb and Zr targets at the Indiana University Cyclotron facility. We hope this data will provide a consistent understanding of nucleon-nucleus and nucleus-nucleus interactions for isovector excitations within a folding model or related picture.

1. Partial support provided by Vanderbilt University and Joint Institute for Heavy Ion Physics, ORNL.

2. Partial support from Joint Institute for Heavy Ion Research, ORNL.

3. Vanderbilt University, Nashville, Tenn.

4. R. J. Peterson, *Phys. Rev. Lett.* **57**, 1550, 2771 (1986).

5. G. R. Satchler, *Nucl. Phys. A* **472**, 215 (1987).

6. S. Shlomo, D. H. Youngblood, T. Udagawa, and T. Tamura, *Phys. Rev. Lett.* **59**, 1054 (1987).

7. J. R. Beene et al., *Phys. Rev. C* **41**, 920 (1990).

8. J. R. Beene et al., *Phys. Rev. C* **39**, 1307 (1989).

9. J. R. Beene and F. E. Bertrand, p. 159 in *The Spectroscopy of Heavy Nuclei 1989*, Inst. Phys. Conf. Ser. No. 105 (Proceedings, Int. Conf. on Spectroscopy of Heavy Nuclei, Crete, Greece, 1989).

HIGH ENERGY TARGET EXCITATIONS IN HEAVY ION INELASTIC SCATTERING¹

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J. E. Lisaniti,³ W. Mittig,⁴ Y. Schutz,⁴
N. Alamanos,⁵ F. Auger,⁵ J. Barrette,⁵
B. Fernandez,⁵ A. Gillibert,⁵ B. Haas,⁶ J. P. Vivien,⁶
and A. M. Nathan⁷

The high energy continuum from inelastic scattering of 84 MeV/nucleon ^{17}O by ^{208}Pb was studied by measuring ^{17}O - γ -ray coincidences. The particle spectra in coincidence with γ rays above ~ 1 MeV show structures up to 45 MeV excitation energy that can be explained in terms of the statistical decay of the highly excited target nucleus. The observation in the γ -ray spectrum of the giant dipole resonance built on excited states in ^{208}Pb confirms that the continuum up to ~ 60 MeV excitation energy is dominated by the excitation of ^{208}Pb and offers the unique possibility of detailed studies of the GDR as a function of excitation energy decoupled from the influence of angular momentum.

1. Abstract of paper submitted to *Physical Review C*.

2. Partial support from Joint Institute for Heavy Ion Research, ORNL.

3. Indiana University Cyclotron Facility, Bloomington.

4. Grand Accélérateur National d'Ions Lourds, Caen, France.

5. Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France.

6. Centre de Recherches Nucléaires, Strasbourg, France.

7. University of Illinois, Champaign.

ISOSPIN CHARACTER OF THE "ISOSCALAR" GIANT QUADRUPOLE RESONANCE IN ^{118}Sn ¹

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The scattering of 84 MeV/nucleon ^{17}O ions by ^{118}Sn has been studied. Inelastic cross sections for excitation of the 2.327-MeV state (3^-), the giant quadrupole resonance (GQR) and the giant monopole resonance (GMR) are reproduced by distorted wave approximation (DWA) calculations using the deformed potential model and assuming isoscalar transitions. A minimum predicted in the angular distribution at $\theta_{\text{cm}} = 1.9^\circ$ from utilization of the small $B(E2)^\uparrow$ strength suggested by π^+/π^- scattering is not apparent in the data.

1. Abstract of paper to be published in *Physical Review C*.

2. Grand Accélérateur National d'Ions Lourds, Caen CEDEX, France.

3. Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette CEDEX, France.

HEAVY-ION COULOMB EXCITATION AND PHOTON DECAY OF THE GIANT DIPOLE RESONANCE IN ^{208}Pb ¹

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Y. Schutz,² J. Barrette,³ N. Alamanos,³ F. Auger,³
B. Fernandez,³ A. Gillibert,³ B. Haas,⁴ and
J. P. Vivien⁴

The excitation and electromagnetic decay of the giant resonance region (8-15 MeV) in ^{208}Pb have been measured with the $^{208}\text{Pb}(^{17}\text{O}, ^{17}\text{O}')$ reaction at 84 MeV/nucleon. The study of coincidences between scattered ^{17}O ions and photon decays to the ^{208}Pb ground state, including angular correlations, serves to isolate the isovector giant dipole resonance and enable us to investigate the mechanisms of its excitation and decay in detail. The angular correlations and yields are accounted for quantitatively by a pure Coulomb excitation model of the reaction process. The

distribution in energy of the ground-state photon decay cross section is well described by an approximate application of the multistep theory of nuclear reactions. The photon coincidence measurements enable us to extract the differential cross sections for the 10.6-MeV giant quadrupole and 13.9-MeV monopole resonances with low uncertainty. An analysis of the Coulomb-nuclear interference for the 10.6-MeV excitation indicates that the ratio of neutron to proton matrix elements, M_n/M_p , is 1.7 ± 0.4 , consistent with a predominantly isoscalar character for the giant quadrupole resonance.

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1. Abstract of published paper: *Phys. Rev. C* **41**, 920 (1990).
 2. Grand Accelérateur National d'Ions Lourds, Caen, France.
 3. Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France.
 4. Centre de Recherches Nucléaires, Strasbourg, France.

COMPOUND AND PRECOMPOUND EFFECTS IN PHOTON DECAY OF THE GIANT DIPOLE RESONANCE¹

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We have investigated the excitation and ground-state photon decay of the giant resonance region in ^{208}Pb and ^{209}Bi due to inelastic scattering of 84 MeV/nucleon ^{17}O . The inelastic spectra are dominated by the isovector giant dipole resonance. The spectra of ^{208}Pb and ^{209}Bi are almost identical in the giant resonance region. We conclude that the resonance strength functions are very nearly the same for these nuclei. Significant differences are, however, found in the distribution of ground-state decay photons from the two nuclei. These differences appear to be due to a large contribution from decay of fully damped compound states in ^{208}Pb .

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1. Abstract of published paper: *Phys. Rev. C* **41**, R1332 (1990).
 2. Present address: Indiana University Cyclotron Facility, Bloomington.
 3. Grand Accelérateur National d'Ions Lourds, Caen, France.
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EXCITATION AND FISSION DECAY OF ^{238}U USING THE ($^{17}\text{O}, ^{17}\text{O}'$) REACTION¹

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R. L. Varner, and A. D'Onofrio⁴

The inelastic scattering of 375 MeV ^{17}O projectiles was used to study the giant resonance region in ^{238}U . The energy, width, and strength of the giant quadrupole resonance (GQR) were extracted from singles spectra and fission probabilities were deduced from singles and coincidence data. Angular correlations between fission fragments and inelastically scattered particles were measured to search for evidence of K conservation in the fission decay of the GQR.

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1. Abstract of published paper: *Phys. Rev. C* **41**, 2620 (1990).
 2. Instrumentation and Controls Division, ORNL.
 3. Present address: Indiana University Cyclotron Facility, Bloomington.
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GIANT MAGNETIC RESONANCES¹

S. Raman, L. W. Fagg,² and R. S. Hicks³

Nuclear magnetic multipole transitions are reviewed, with particular emphasis on transitions having single-particle character. The distribution of magnetic transition strength with regard to excitation energy and nuclear mass is discussed, as are properties

of magnetic transition densities such as radial dependence, the relative contributions of spin and orbital currents, and isospin structure. Experimental information on these properties is gathered by means of the separate and synergetic use of reactions that include the scattering of intermediate-energy polarized and unpolarized protons, comparative π^+ and π^- scattering, high-resolution electron scattering, and resonance fluorescence with tagged and polarized photons. The diverse sensitivities of each of these probes are analysed, and typical results are shown. The progress that has been made toward reaching a theoretical understanding of the spectrum of magnetic excitations is also outlined.

1. Abstract of a book chapter to be published in *Electric and Magnetic Giant Resonances in Nuclei*, edited by J. Speth (World Scientific, Singapore, 1990).

2. Catholic University of America, Washington, DC.

3. University of Massachusetts, Amherst, Massachusetts.

INVESTIGATION OF ISOSPIN CHARACTER OF BOUND STATES IN 204,206,208Pb

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M. L. Halbert, D. J. Horen, G. R. Satchler,
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As a result of the suggestion resulting from a series of inelastic π^-/π^+ measurements² that the giant quadrupole resonance (GQR) contains a significant isovector component, we have performed heavy-ion inelastic scattering measurements³ on ^{208}Pb and ^{118}Sn . In this technique, use is made of the interference between the nuclear and Coulomb amplitudes for exciting a nuclear state to determine the ratio between the neutron and proton multipole transition matrix elements M_n/M_p , which is a measure of the isospin admixture. Our inelastic

heavy-ion studies gave results which indicated that the GQR is nearly "pure" isoscalar.

In this work, we decided to more stringently test the deformed potential model which is an inherent part of our analysis of the heavy-ion data. To this end, we have measured scattering of 375-MeV ^{17}O ions from the coupled machine operation at HHIRF by targets of 204,206,208Pb. The broad range spectrograph was used to make measurements of the elastic and inelastic scattering from bound states over the laboratory angle range from 5.5-19.5°, which includes angles well inside the grazing angle. All data were taken with the elastic peak on the focal plane.

Analyses of the data show that angular distributions for the well known collective states at 2.618 MeV (3^-) and 4.085 MeV (2^+) in ^{208}Pb (see Fig. 2.1a and 2.1b, respectively) are well described by DWA calculations using the deformed potential model, and yield $M_n/M_p \approx N/Z$, as expected for isoscalar excitations. To reproduce the angular distributions for excitation of the first 2^+ state at 0.899 MeV in ^{204}Pb (and the 0.803-MeV 2^+ state ^{206}Pb), a value of $M_n/M_p \approx 2.5$ (see Fig. 2.1c) which is considerably larger than $N/Z = 1.49$ is required. This result is in reasonable agreement with a simple nuclear structure calculation which suggests $M_n/M_p \approx 2.0$ (Ref. 4).

Should we find agreement with M_n/M_p predictions from a more refined calculation, our confidence in use of a single-probe which makes use of the nuclear-Coulomb interference will be enhanced.

1. Partial support from Joint Institute for Heavy Ion Research, ORNL.

2. S. J. Seestrom-Morris et al., *Phys. Rev. C* 33, 1847 (1986); J. L. Ullmann et al., *Phys. Rev. C* 35, 1099 (1987); D. S. Oakley et al., *Phys. Rev. C* 40, 859 (1989).

3. D. J. Horen, J. R. Beene, and F. E. Bertrand, *Phys. Rev. C* 37, 888 (1988); J. R. Beene et al., *Phys. Rev. C* 41, 920 (1990); D. J. Horen et al., "Investigation of Isospin Character of Bound States in 204,206,208Pb," this report.

4. V. R. Brown, private communication.

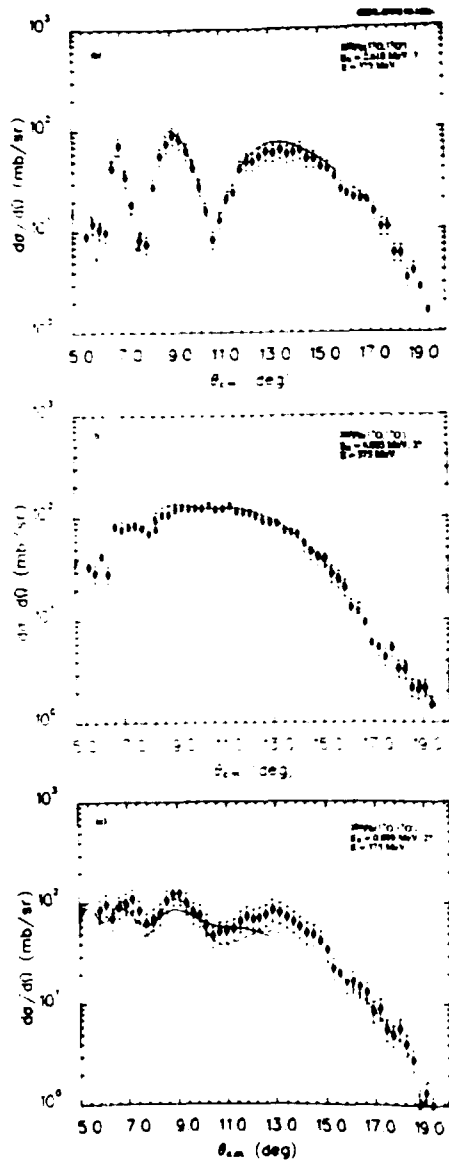


Fig. 2.1. (a,b) Differential cross sections for excitation of the collective 3^+ , 2.618-MeV, 2^+ , 4.085-MeV states in ^{208}Pb , respectively. The solid curves are coupled channels calculations using the deformed potential model. (c) Differential cross sections for excitation of the first 2^+ state in ^{204}Pb at 0.899 MeV. (The data represent the target cross section which includes contributions from $^{206,207}\text{Pb}$ and is not corrected for the abundance of ^{204}Pb in the target.) The solid and dashed curves are coupled channels calculations using $M_N/M_p = 1.49$ and 3.0 respectively. The calculated curves have been properly scaled to the data.

ANALYZING POWERS AND CROSS SECTIONS OF INCLUSIVE POLARIZED PROTON SCATTERING ON ^{208}Pb ¹

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D. M. Drake,³ I. Bergqvist,⁴ A. Brockstedt,⁴
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M. Vetterli,⁶ and M. J. Iqbal⁶

Inclusive polarized proton-nucleus scattering on ^{208}Pb has been studied at 290 and 500 MeV. The measurements cover a broad range (0-250 MeV) of excitation energy over the 4° - 27° angular range. The measured analyzing powers and cross sections for the continuum were compared with recent relativistic and nonrelativistic distorted-wave impulse approximation calculations. The cross section in the continuum region is found to be dominated by single-step quasi-free scattering. Differences of up to 40% between the analyzing powers measured at the quasi-free peak as opposed to free NN values strongly support the relativistic impulse approximation predictions for the quasi-free region, and indicate the presence of relativistic medium effects. Analyzing powers and cross sections of several low-lying states were compared with both nonrelativistic and relativistic distorted-wave Born approximation predictions.

1. Abstract of published paper: *Nucl. Phys. A* **505**, 670 (1989).

2. Oregon State University, Corvallis.

3. University of Oregon, Eugene.

4. Luna University, Sweden.

5. Indiana University Cyclotron Facility, Bloomington.

6. TRIUMF, Vancouver, B.C., Canada.

^{24}Mg NUCLEAR MOMENTS FROM $^{24}\text{Mg}(200\text{ MeV}) + ^{208}\text{Pb}$ SCATTERING¹

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D. L. Humphrey,² and T. VanCleve²

Differential cross sections for exciting the low-lying states in ^{24}Mg by heavy-ion inelastic scattering were measured with a new technique that uses a 4π γ -ray detector in coincidence with charged-particle detectors. The resulting data were subjected to a

coupled-channels analysis to obtain a set of E2 and E4 matrix elements for exciting the 2_1^+ (1.37 MeV), 4_1^+ (4.12 MeV), and 2_2^+ (4.24 MeV) states of ^{24}Mg as well as the interconnecting and self-coupling matrix elements for these states. Our results disagree with electron scattering measurements for the charge shape of ^{24}Mg . The data on the 2_2^+ (4.24 MeV) state is not well accounted for by the asymmetric rotor model.

1. Abstract of published paper: *Phys. Rev. C* **40**, 2065 (1989).

2. Western Kentucky University, Bowling Green.

PARTICLE- γ CORRELATION DETERMINATION OF STATIC QUADRUPOLE MOMENTS¹

E. E. Gross, D. C. Hensley, and J. R. Beene

A complete particle γ -ray angular correlation has been measured for the decay of the first 2^+ state of ^{24}Mg excited by $^{24}\text{Mg}(200 \text{ MeV}) + ^{208}\text{Pb}$. The particle- γ -ray correlation, expressed as alignment tensors, proves to be particularly sensitive to the static quadrupole moment of the 2_1^+ state. The derived value of the 2_1^+ static quadrupole moment is $Q_2 = (-29 \pm 3) e \text{ fm}^2$ which is (1.56 ± 0.16) times larger than the rotational value.

1. Abstract of published paper: *Phys. Rev. C* **42**, R471 (1990).

^{26}Mg NUCLEAR STRUCTURE FROM $^{26}\text{Mg}(200 \text{ MeV}) + ^{208}\text{Pb}$ SCATTERING

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F. E. Bertrand, M. L. Halbert, G. Vourvopoulos,¹
and D. L. Humphrey¹*

In a prior publication,² we presented a new technique for performing inelastic scattering experiments and applied the method to the low-lying states of ^{24}Mg excited in $^{24}\text{Mg}(200 \text{ MeV}) + ^{208}\text{Pb}$ scattering. The technique consists in using a 4π γ -ray detector, the Spin Spectrometer (S.S.), to detect the decay γ -rays in coincidence with scattered

projectiles detected in position-sensitive solid-state detectors. The γ -ray detectors provide the necessary resolution to resolve the excited states while the solid-state detectors provide the information for the differential cross section. The technique also provides particle- γ angular correlation information which proves to be sensitive to the static quadrupole moment of the first 2^+ state.³ Recently the method has been applied to the low-lying states of ^{26}Mg . In addition to obtaining differential cross sections for elastic scattering and for exciting the 2_1^+ (1.81 MeV), 2_2^+ (2.94 MeV), 4_1^+ (4.32 MeV), and 4_2^+ (4.90 MeV) states, we also obtained particle- γ angular correlation data for all these excited states except the 4_1^+ state. The particle- γ angular correlation data obtained for the second 2^+ and second 4^+ states are the first of their kind covering a large angular range.

This extensive data set is being subjected to a rotational-model coupled-channels analysis. As in the case of the previous analysis of similar data for ^{24}Mg (Ref. 2), we find the particle- γ angular correlation data for the decay of the first 2^+ state to be particularly important in determining the static quadrupole moment of this state. The calculation gives an excellent account of both the differential cross section and the particle- γ angular correlation data. From this analysis we obtain $M(E2; 0_1^+ \leftrightarrow 2_1^+) = (-16.79 \pm 0.18) e \text{ fm}^2$ and $Q_2 = (-20.9 \pm 1.9) e \text{ fm}^2$. The $ME(2)$ value is 4% smaller than the "adopted" Coulomb excitation value⁴ and the static quadrupole moment, Q_2 , is 41% larger than rigid-rotor and shell-model expectations.

The coupled-channels analysis gives a good account of the shape of the 4_2^+ (4.90 MeV) state but fails in the case of the 4_1^+ (4.32 MeV) state. We conclude from this that the 4_2^+ state is the ground state member of the rotational band and that the 4_1^+ state is not a collective state. From the fit to the 4_2^+ state we obtain $M(E4; 0_1^+ \leftrightarrow 4_2^+) = (95 \pm 10) e \text{ fm}^4$ for the hexadecapole moment of the ground state band. The second 2^+ state has been interpreted as evidence for a triaxial shape for ^{26}Mg (Ref. 5). Therefore we attempted an asymmetric-rotor model⁶ analysis as well as a symmetric-rotor model analysis. Although the asymmetric-rotor model qualitatively accounts for the shape of the 2_2^+ differential cross section, the sign of the E2 matrix element between the two 2^+ states predicted by the model is opposite

to the sign deduced from the analysis using rotational-model form factors and the predicted 4^+ cross section is a factor of three larger than either of the two observed 4^+ states. Furthermore, the γ parameter of the theory⁵ required for the best fit to the magnitude of the measured 2_2^+ cross section is 6° whereas the value of γ to account for the energy spacing of the two 2^+ states is near 30° . We conclude that the present data and analysis does not offer much support for triaxiality in ^{26}Mg .

1. Western Kentucky University, Bowling Green.
2. D. C. Hensley, E. E. Gross, M. L. Halbert, J. R. Beene, F. E. Bertrand, G. Vourvopoulos, D. L. Humphrey, and T. Van Cleve, *Phys. Rev. C* **40**, 2065 (1989).
3. E. E. Gross, D. C. Hensley, and J. R. Beene, *Phys. Rev. C* **42**, R471 (1990).
4. S. Raman, C. H. Malarkey, W. T. Milner, C. W. Nestor, Jr., and P. H. Stelson, *Atomic Nuclear Data Tables* **36**, 1 (1987).
5. D. Kurath, *Phys. Rev.* **5**, 768 (1972).
6. A. S. Davydov and G. F. Filippov, *Nucl. Phys.* **8**, 237 (1978).

ELASTIC MAGNETIC ELECTRON SCATTERING FROM ^{41}Ca ¹

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Y. Han,² R. S. Hicks,² R. A. Miskimen,²
G. A. Peterson,² S. H. Rokni,² B. Frois,³
J. Martino,³ S. Platchkov,³ C. N. Papanicolas,⁴
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The elastic magnetic form factor of ^{41}Ca has been determined by 180° electron scattering in the momentum transfer range of 0.9 to 2.0 fm^{-1} . An analysis of the data indicates that the amplitudes of the $M3$ and $M5$ multipoles are quenched by factors of 0.57 ± 0.16 and 0.68 ± 0.07 relative to the simple shell model. In contrast, the magnitude of the $M7$ form factor is in good accord with this model. Core polarization and meson exchange currents calculations give improved agreement with the data for all multipoles, and suggest that the quenching of the $M3$ and $M5$ multipoles is largely due to core polarization. Our results and previous higher momentum transfer

data were used to obtain the rms radius of the $1f_{7/2}$ neutron orbit. After correcting for core polarization and meson exchange currents, the radius was found to be $3.96 \pm 0.05\text{ fm}$, a value slightly smaller than that obtained from mean-field calculations.

1. Abstract of paper to be published in *Physical Review C*.
2. University of Massachusetts, Amherst.
3. C.E.N. Saclay, Gif-sur-Yvette, France.
4. University of Illinois, Champaign.
5. M.I.T.-Bates Linear Accelerator Center, Middleton, Massachusetts.
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MEASUREMENT OF $A_y(\theta)$ FOR $n + ^{208}\text{Pb}$ FROM 6 TO 10 MeV AND THE NEUTRON-NUCLEUS INTERACTION OVER THE ENERGY RANGE FROM BOUND-STATES AT -17 MeV UP TO SCATTERING AT 40 MeV¹

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High-accuracy measurements of $A_y(\theta)$ data for elastic scattering and inelastic scattering to the first-excited state for $n + ^{208}\text{Pb}$ have been performed at 6, 7, 8, 9, and 10 MeV. In addition, $\sigma(\theta)$ was measured at 9 MeV. These data provide an important subset for the growing data base for the $n + ^{208}\text{Pb}$ system from bound-state energies to energies above 40 MeV, the limit of the range of interest here. This data base has been interpreted via several approaches. First, a conventional Woods-Saxon spherical optical was used to obtain three potential representations for the energy range from 4 to 40 MeV: "best-fits" at each energy, constant geometry global fit with linear energy dependences for the potential strengths for the range 4.0 to 40 MeV, and an extension of the latter model to allow a linear energy dependence on the radii and diffusenesses. A tendency for an imaginary spin-orbit interaction was seen in these analyses. Second, the dispersion relation was introduced into the spherical optical model to obtain a more "realistic" representation. In our approach, the strength and shape of the real potential was modified by calculating the dispersion-relation contributions that originate

from the presence of the surface and volume imaginary terms. Two potentials were developed, one based only on the scattering data (from 4.0 to 40 MeV) and another that was based also on bound-state information down to -17 MeV. In addition, the data were compared to earlier conventional and dispersion-relation models. One of the latter of these included ℓ -dependence in the absorptive surface term, and we applied this model in the 6- to 10-MeV region to describe both the $\sigma(\theta)$ and the new $A_y(\theta)$. A reasonably good overall description was obtained by all the models; however, only the ℓ -dependent model came close to giving a detailed agreement to the data around 7 MeV, a region where some abnormal angular dependencies occur in the data.

1. Abstract of a paper to be submitted to *Physical Review C*.
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THE (p,n) REACTION ON Li ISOTOPES FOR $E_p = 60$ -200 MeV¹

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Differential cross section angular distributions for the ${}^6\text{Li}(p,n){}^6\text{Be}$ reactions have been measured at energies between 60 and 200 MeV. The experimental angular distributions are analyzed using a microscopic distorted wave impulse approximation. The results of self-consistent microscopic distorted wave calculations based on a complete set of weak and electromagnetic data for the mass 6 and 7 systems are also presented. Total observed Gamow-Teller strength up to about 40 MeV excitation energy is reported. Energy dependence of the σ_T and τ effective interaction terms are presented up to 200 MeV. The measured (p,n) cross sections for the ${}^7\text{Be}$ (gs) and ${}^7\text{Be}$ (0.43 MeV) transitions are used to obtain the branching ratio of the ${}^7\text{Be}$ (gs) decay to the gs and 0.478 MeV states in ${}^7\text{Li}$. Zero degree polarization transfer (D_{NN}) data at $E_p = 80, 120, 160$, and 200 MeV are reported for the ${}^6\text{Li}(p,n){}^6\text{Be}$ (gs) and for the ${}^7\text{Li}(p,n){}^7\text{Be}$ (gs + 0.43 MeV) reactions. Energy dependence of total and zero degree differential cross section for the ${}^7\text{Li}(p,n){}^7\text{Be}$

(gs + 0.43 MeV) transitions are reported. Finally a comparison is presented for the (n,p), (p,p) and (p,n) reaction in ${}^6\text{Li}$ populating isospin triplets.

1. Abstract of published paper: *Phys. Rev. C* **41**, 1920 (1990).
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ZERO-DEGREE CROSS SECTIONS FOR THE ${}^7\text{Li}(p,n){}^7\text{Be}$ (g.s. + 0.43-MeV) REACTION IN THE ENERGY RANGE 80 MeV to 790 MeV¹

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Differential-cross-section distributions for the ${}^7\text{Li}(p,n){}^7\text{Be}$ (g.s. + 0.43-MeV) reaction have been measured for $E_p = 80, 120, 160, 200, 494, 644$, and 790 MeV. These distributions have been integrated and normalized to independent values for the total cross section obtained from parametrizations of ${}^7\text{Li}(p,n)$ activation measurements. Zero-degree cross sections obtained from this normalization are reported.

1. Abstract of published paper: *Phys. Rev. C* **41**, 2548 (1990).
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GAMOW-TELLER TRANSITION STRENGTHS FROM THE $^{11}\text{B}(\text{p},\text{n})^{11}\text{C}$ REACTION IN THE ENERGY RANGE 160 MeV to 795 MeV¹

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Zero-degree cross sections have been measured for the $^{11}\text{B}(\text{p},\text{n})^{11}\text{C}$ reaction at bombarding energies of $E_p = 160, 200, 494, 644$, and 795 MeV. In addition, spectra have been obtained at lab scattering angles of 3° and 5° at 494 MeV, and the transverse spin-flip probability at zero degrees has been measured for $E_p = 160$ MeV. These data are used to obtain estimates of the Gamow-Teller transition strength to final states in ^{11}C up to an excitation energy of $E_x \approx 14$ MeV. The uncertainty (one standard deviation) in the extracted transition strengths is estimated to be in the range 2-8%. Measured cross sections for the first four excited states in ^{11}C have been compared with distorted-waves impulse approximation calculations. In this comparison, no evidence is found in the cross-section data for certain effects associated with knock-on exchange and non-central interactions.

1- Abstract of published paper: *Phys. Rev. C* **42**, 935 (1990).

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A GLOBAL NUCLEON OPTICAL MODEL POTENTIAL¹

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We describe a new parameterization of the nucleon-nucleus optical model potential based on data for $A = 40$ to 209 , proton energies of 16 to 65 MeV and neutron energies of 10 to 26 MeV, including extensive polarized-beam data. This parameterization, called CH89, is based on current understanding of the basis of the optical potential, such as the folding model and nuclear-matter approaches. It differs significantly from previous global parameterizations, especially in the weakness of the isovector potential, the parameterization of potential radii, and the smooth variation of imaginary potential depths with energy. We also describe an optical-model-parameter search system, MINOPT, based on the minimization program MINUIT. It is applied to simultaneously analyze a large database of nearly 300 carefully selected angular distributions. Parameter uncertainties and correlations between parameters are estimated by using the non-parametric statistical technique known as the bootstrap. CH89 is intended to serve as a starting point for definitive tests of models of the nucleon-nucleus interaction, and to be of immediate use for applications.

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LOW-LYING COLLECTIVE QUADRUPOLE AND OCTUPOLE STRENGTHS IN EVEN-EVEN NUCLEI¹

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The $B(E2)\uparrow$ values for the first 2^+ state of even-even nuclei in the $Z \geq 50$ region are compared with the predictions of several theoretical models. Comparative estimates of the overall agreement with

the data are provided. Gaps and discrepancies in the data and examples that show interesting features such as shape changes are discussed. The $B(E2)^\dagger$ values are examined critically to search for the dynamical Pauli effects predicted by the Fermion Dynamic Symmetry model. The empirical $B(E2)^\dagger$ and $B(E3)^\dagger$ systematics are employed to obtain a measure of the harmonicity of the quadrupole and octupole vibrations. The fraction of the energy-weighted sum-rule strength exhausted by the sum of all known low-lying 2^+ states below 2.3 MeV is found to be surprisingly constant in the $60 < A < 250$ region except near closed shells.

1. Abstract of paper: Submitted to *Physical Review C*.
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TESTING THE PARAMETERS OF THE "UNIVERSAL" WOODS-SAXON POTENTIAL WITH $B(E2; 0_1^+ \rightarrow 2_1^+)$ VALUES AND NUCLEON SEPARATION ENERGIES¹

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The idea of "universality" of an average nuclear field introduced earlier has been applied and tested in the calculations of $B(E2; 0_1^+ \rightarrow 2_1^+)$ values and nucleon separation energies for nuclei in the $Z \geq 52$, $A \geq 120$ region. A good description is obtained using a single "universal" choice of 12 constants defining the deformed Woods-Saxon nuclear average field.

1. Abstract of published paper: *Phys. Rev. C* 40, 2282 (1989).
2. Joint Institute for Heavy-Ion Research, ORNL and Nuclear Research Centre-Negev, Beer Sheva, Israel.
3. Joint Institute for Heavy-Ion Research, ORNL and University Louis Pasteur, Strasbourg, France.

NUCLEAR STRUCTURE STUDIES VIA TRANSFER, CAPTURE, AND COULOMB EXCITATION REACTIONS

COULOMB EXCITATION OF ^{159}Tb AND THE SPECTROSCOPY OF THE PROTON $3/2^+[411]$ NILSSON CONFIGURATION¹

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The decay scheme of the ground-state configuration of $^{159}\text{Tb}_{94}$ has been extended to $1^\circ = 37/2^+$ (tentatively to $39/2^+$) by Coulomb exciting ^{159}Tb using a 981.7 MeV ^{208}Pb beam. A band crossing, associated with the excitation of a pair of $i_{13/2}$ quasineutrons, was observed for the first time in

a rotational sequence based on a $3/2^+[411]$ quasiproton. The basis of the observed small signature dependence of the energies corresponding to this configuration is discussed, as is the effect of an odd $3/2^+[411]$ quasiproton on the moment of inertia.

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BREAKUP OF ${}^7\text{Li}$ NEAR THE α -t THRESHOLD AND A POSSIBLE PROBE OF RADIATIVE-CAPTURE PROCESSES¹

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Breakup of 63-MeV and 42-MeV ${}^7\text{Li}$ near the α -t threshold is examined from the astrophysical point of view. A new approach is made to extract indirectly astrophysical S factors. The S factors are compared with those deduced from radiative-capture measurements. It is shown that the energy dependence favors the recent capture data of Schröder et al.

1. Abstract of paper: *Phys. Rev. Lett.* **65**, 847 (1990).
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NEARLY COMPLETE LEVEL SCHEME OF ${}^{116}\text{Sn}$ BELOW 4.3 MeV¹

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The level scheme of ${}^{116}\text{Sn}$ has been studied by combining the results of ${}^{115}\text{Sn}(n,\gamma){}^{116}\text{Sn}$ and ${}^{116}\text{Sn}(n,n'\gamma){}^{116}\text{Sn}$ experiments. Both experiments were performed using isotopically enriched samples and Ge γ -ray detectors. Based on the thresholds of γ -ray excitation functions measured for the ${}^{116}\text{Sn}(n,n'\gamma)$ reaction and the precise γ -ray energies from the capture reaction, 100 levels were observed below 4.3-MeV excitation energy. Approximately half of these were not known previously. Forty-eight of these levels have unique or tentative spin-parity assignments, and for ten more the spin has been restricted to a single value. The spin-parity for most

other levels below 4.3 MeV excitation has been restricted to a few values. These spin-parity assignments and limitations were derived mainly from $(n,n'\gamma)$ angular distribution measurements, together with additional information obtained from the cross section magnitudes in both experiments. Above 4.3-MeV excitation energy, 55 additional levels are proposed, based only on the ${}^{115}\text{Sn}(n,\gamma)$ results. No J^π information is available for these higher-lying levels beyond the fact that they most probably all have $J \leq 4$. The level scheme below 4.3 MeV from the current work, together with known high-spin levels up to 5.4 MeV seen in other experiments, are compared to the combined predictions of the two-broken-pair model, the Interacting Boson model, and the deformed collective model. In addition, several states have been phenomenologically identified as proton $1p$ - $1h$ and collective quadrupole-octupole two-phonon excitations. It is concluded from the good agreement between experiment and these models that all levels in ${}^{116}\text{Sn}$ with $J \leq 6$ up to an excitation of 4.0 MeV and $J \leq 3$ up to 4.3 MeV may have been experimentally identified. The nearest-neighbor spacing distribution is intermediate between that of a Gaussian orthogonal ensemble and that of a Poisson distribution, with a slight preference for the former. The neutron separation energy was determined to be 9563.47 ± 0.11 keV.

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NUCLEAR STRUCTURE VIA COMPOUND NUCLEUS REACTIONS

HIGH SPIN STATES IN ^{80}Rb

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High-spin band structures of the neutron-deficient nuclei in the mass $A = 80$ region, where protons and neutrons occupy the same shell, can provide important information regarding the p-n interaction, and shape-driving forces of the $g_{9/2}$ orbitals. These considerations, as well as recent reports of unusual behavior of the structure of high-spin bands in $^{78,79}\text{Rb}$ nuclei motivated the present study of the doubly odd nucleus ^{80}Rb .

The level scheme of ^{80}Rb has been studied previously by Behar et al.⁵

Raghavan et al.⁶ have also reported the presence of an isomeric state with a half life of $1.60(2) \mu\text{s}$ in this nucleus which feeds most of the states established in Ref. 5. From this measurement and the known properties of ^{80}Rb , it may be concluded that the isomeric state must lie above the state at 486 keV. Since transitions that deexcite the isomeric state have not been observed, we conclude that the isomer feeds the spin $I = (4)$ or (5) excited states via one or more low-energy, highly converted transitions. This suggests a spin value of approximately 6 or 7 for the isomer.

In the present study, we used the $^{52}\text{Cr}(^{34}\text{S}, \alpha np)$ reaction at a beam energy of 130 MeV. The experimental setup consisted of the ORNL Compton Suppression Spectrometer (18 Ge), the Spin Spectrometer, and the 4π CsI Dwarf Ball of Washington University for detection of light charged particles. We have identified two signature-partner cascades with smoothly increasing transition energies (Fig. 2.2). Assignment of this rotational structure to ^{80}Rb was made on the basis of the following arguments: (a) these transitions are in coincidence with one α and one proton, but not two α 's; (b) excitation functions taken at the TANDAR laboratory using the $^{65}\text{Cu}(^{19}\text{F}, 3n)$ reaction show that

the behavior of the 157-, 891-, and 472-keV transitions is similar to the other known transitions in ^{80}Kr ; and (c) the singles spectrum from the $^{79}\text{Br}(\alpha, 3n)$ reaction of Ref. 5 shows an unidentified peak at 156.5 keV. This analysis suggests that the observed rotational band belongs to ^{80}Rb and probably feeds the isomeric state.

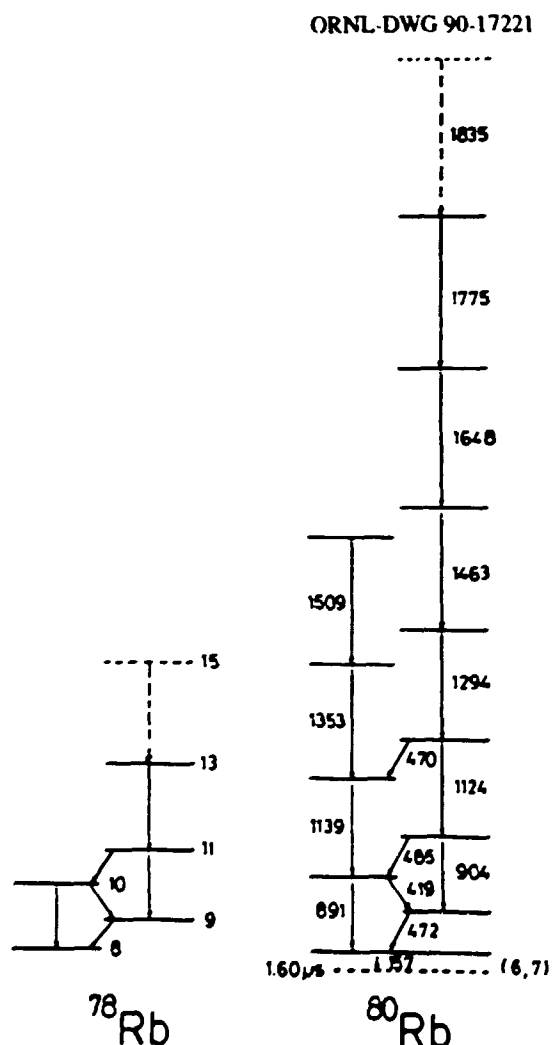


Fig. 2.2. Partial level scheme of ^{80}Rb .

The dynamical moments of inertia, $J^{(2)}$, of the yrast sequences in $^{78,79,80}\text{Rb}$ nuclei show a smooth behavior in the frequency range of $\hbar\omega \leq 0.6$ MeV, where the first $\pi g_{9/2}$ crossing is observed in the isotones ^{79}Kr , ^{81}Sr , as well as the negative-parity band of ^{81}Rb . This suggests $\pi g_{9/2}$ orbital as the likely proton configuration for the observed band. Since both $\pi g_{9/2}$ and $\nu g_{9/2}$ bands in the neighboring nuclei show large signature splittings, the small signature splitting of the observed band rules out involvement of the $\nu g_{9/2}$ orbital. Although both the $[301]1/2$ and $[303]5/2$ neutron orbitals have a small signature splitting, only the latter configuration can give rise to a high-spin isomeric state ($I^\pi = 6^-$).

Interestingly, the energies of the γ rays within the observed band fall very closely to the average energies of the consecutive transitions in the yrast band of ^{78}Rb (Ref. 7). On the basis of this similarity, we can deduce a spin value of $I \approx 8$ for the state fed by the 157-keV transition. This suggests the presence of unobserved low-energy γ rays that connect this band to the isomeric state. Further studies using pulsed beam and gamma-electron coincidence measurements are planned to investigate the relationship of the isomer and high-spin band.

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5. M. Behar et al., *Nucl. Phys. A* **287**, 255 (1977).

6. R. S. Raghavan et al., Progress Report, Rutgers University, 1977-1979.

7. J. H. McNeill et al., Manchester Nuclear Physics Report, 1987-1988.

SHAPE COEXISTENCE AND DISAPPEARANCE OF PAIRING CORRELATIONS IN ^{82}Sr ¹

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Extensive high-spin band structures in ^{82}Sr have been established using proton- γ - γ coincidence techniques. On the basis of the Woods-Saxon cranking calculations with pairing, four of these bands are interpreted to have prolate, oblate, or triaxial shapes. Pairing correlations are predicted to be very weak at high spins in this nucleus, and calculations with no static pairing successfully reproduce the experimentally observed crossing frequencies and alignments despite the fact that none of the bands displays a rigid-rotor behavior. It is concluded that observation of rigid-rotor behavior is neither necessary nor sufficient for the disappearance of static pairing in nuclei.

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ROTATIONAL DAMPING WIDTH FROM A TRIPLE E_γ CORRELATION STUDY OF ^{130}Ce

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The γ - γ correlation method has been used to study the continuum γ rays. From these studies, the distribution of the energy difference of two successive γ -ray transitions can be studied as a function of the

γ -ray energy. The results² indicate that there are at least two components in the distribution of the energy difference. One component with a narrow width about 15-20 keV has been interpreted as collective cascades of discrete transitions near the yrast line. The intensity of this narrow component represents only a small fraction of the total γ -ray cascade. Therefore, it was deduced that a second broader component must exist. These γ rays are most likely from regions of higher excitation energy and their broad energy distribution is the result of "Rotational Damping."³

So far the distribution of the broad component has not been observed and there is no direct measurement of its width. Estimates from rotational damping calculations³ give values of about 200 keV which make it very difficult to observe in twofold coincidence measurements. The broad-width cascade feeds the region with narrow widths. From the feeding pattern, it is possible to derive the average excitation energy of the region with the wide width. These studies require triple γ -ray energy correlation data with good statistics.

A triple γ -ray energy correlation study was carried out for ^{130}Ce by using a 152-MeV beam of ^{34}S on a ^{100}Mo target from the HHIRF tandem accelerator. The γ rays were detected in 18 Compton-suppressed Ge detectors placed at a distance of about 12 cm from the target. By placing energy gates on two γ rays, "double gated" spectra were generated from the triple coincidence data. By varying the relative energy of the two gates, it is possible to enhance different decay paths of the cascade. For example, gates with the same energy will exclude the cascade with the narrow width. On the other hand, two narrow gates separated by an energy corresponding to the difference between two successive transitions in a rotational sequence will enhance the cascade with narrow width. The left-portion of Fig. 2.3 shows a double-gated spectrum (gates of 1.07-1.13 and 1.10-1.16 MeV) and the total projection of a single-gated, two-dimensional spectrum. The spectra show features of cascades with both the narrow and wide widths. Similar spectra obtained from a simulation are shown in the right portion of Fig. 2.3. To reproduce the experimental spectra, it is necessary to include a branching factor of 0.03 from the wide width cascade to the cascade with narrow width. Figure 2.4 shows the distribution of

the rotational damping width, Γ_{rot} , as a function of E_{γ} from an analysis of the single-gated spectra.

1. Vanderbilt University, Nashville.
2. F. S. Stevens et al., *Phys. Rev. Lett.* **58**, 2186 (1987); *Phys. Rev. C* **37**, 2927 (1988).
3. B. Lauritzen, T. Dossing, and R. A. Broglia, *Nucl. Phys. A* **457**, 61 (1986).

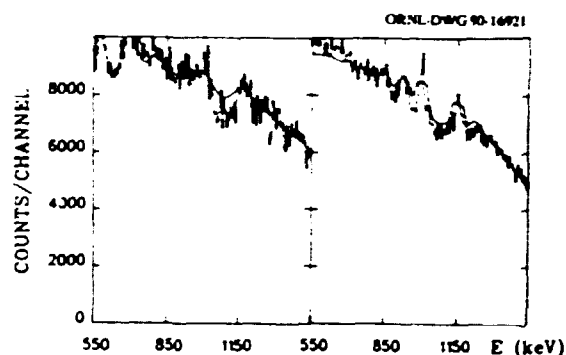


Fig. 2.3. The left panel shows an experimental double-gated spectrum and the total projection of a single-gated spectrum (smooth curve). The right panel shows the same spectra from simulation calculations.

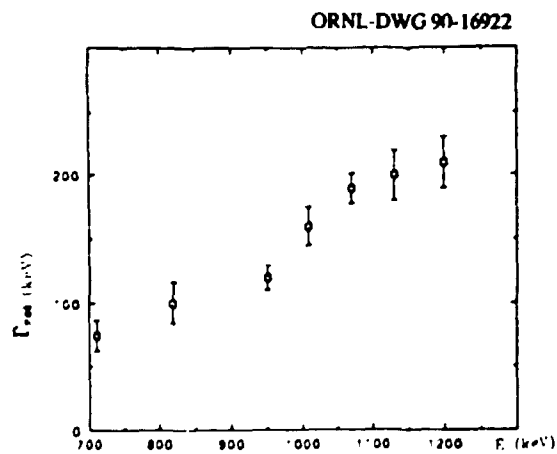


Fig. 2.4. Experimental values of Γ_{rot} as a function of γ -transition energy.

INTEGER ALIGNMENT AND STRONG COUPLING LIMIT IN SUPERDEFORMED NUCLEI

R. Wyss¹ and S. Pilotte²

During the last year, many superdeformed (SD) bands with almost identical moment of inertia have been observed, the first being reported in the mass $A = 150$ region.³ The identical SD bands of ^{152}Dy (yrast) and of ^{151}Tb (excited) have been discussed as resulting from complete decoupling or alignment of pseudo spin involving the $[301]1/2$ Nilsson orbital, related to the pseudo $\text{SU}(3)$ symmetry.⁴ For the very elongated shapes considered here, most orbitals remain strongly coupled to the core. The Coriolis interaction matrix elements are small compared to the level splitting in the single particle potential (see also Ref. 4). Therefore, the strong coupling limit is, in general, valid for superdeformed states. A decoupling parameter close to zero is what one expects for most orbitals (the $\Omega = 1/2$ and intruder orbitals excluded).

For many SD nuclei in the Hg region, the moments of inertia, $\mathcal{J}$, are similar to ^{192}Hg .^{5,6} One can thus take the transition energies E_γ of ^{192}Hg as a reference for comparison with the nearest transition energies E_γ^* of a neighboring nucleus. It follows from the Rotor Hamiltonian that for bands with the same moment of inertia

$$E_\gamma^* - E_\gamma = \Delta E_\gamma = 2 \frac{\hbar^2}{\mathcal{J}} \Delta I,$$

where ΔI is the difference in spin between the two nuclei.

The quantity $\Delta \hbar \omega / (\hbar^2 / \mathcal{J})$ or $\Delta E / (2\hbar^2 / \mathcal{J})$ has been defined previously as the incremental alignment Δi .⁵ Strongly coupled bands have no initial alignment, $i_1 = 0$, and $\Delta I = \Delta i + 2n$ (Δi is defined within multiples of 2 because a band can start with spin $1/2$, $5/2$, and so on). When comparing transition energies of an even-even nucleus with a strongly coupled band of a neighboring nucleus, one finds that the incremental alignment Δi approaches one for an odd-spin sequence in a K band but zero in the even-spin sequence. Similarly, Δi is $\pm 1/2$ in the sequence of an odd-even nucleus. (One should note that the sign of Δi is opposite to that given in Ref. 5, where the alignment i has been defined as $i = \Delta i + \Delta I$. This

definition will always lead to an integer alignment i in strongly coupled bands with similar moments of inertia, because both Δi and ΔI are half integer.)

Striking examples of a strongly coupled sequence are the two excited SD bands of ^{153}Dy which have moments of inertia identical to those in ^{152}Dy (Ref. 3). In ^{152}Dy , $4\hbar^2/\mathcal{J}$ has a value of 47 keV for almost the whole band, and ΔE_γ is $\pm(11-12)$ keV between the nearest transitions in ^{152}Dy and ^{153}Dy , yielding an incremental alignment of $\pm 1/2$. The band in ^{153}Dy has been discussed as being strongly coupled and therefore having a decoupling parameter of zero.⁴ An incremental alignment of $\pm 1/2$ is thus a sign for the strong coupling limit to be valid and only shows the spin contribution of the odd particle as compared to the even-even core. It is "natural" because strongly coupled orbitals do not have any alignment at zero frequency [$i_0(\omega = 0) = 0$]. It is not a sign of integer alignment.

1. Joint Institute for Heavy Ion Research, ORNL.
2. University of Tennessee, Knoxville.
3. T. Byrski et al., *Phys. Rev. Lett.* **64**, 1650 (1990).
4. W. Nazarewicz, P. J. Twin, P. Fallon, and J. D. Garrett, *Phys. Rev. Lett.* **64**, 1654 (1990).
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THE SHAPE POLARIZATION OF ODD-Z ORBITALS IN RARE EARTH NUCLEI

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The shape of the atomic nucleus is intimately related to the occupation of valence shell orbitals. The existence of nuclear pair correlations leads to shape polarization effects which can be studied by comparing experimental quantities sensitive to the nuclear shape in neighboring even-even and odd-A nuclei. Two such examples are considered: (i) Transition quadrupole moments, Q_1 , extracted from measured lifetimes for the odd-Z nucleus ^{157}Ho are systematically lower in the spin range $I = 8-16$ than

for either of the neighboring isotones, ^{156}Dy and ^{158}Er (Fig. 2.5); (ii) Band crossing frequencies, $\hbar\omega_c$, corresponding to the excitation of the lowest pair of quasineutrons in the stably-deformed (heavier) Lu isotopes are systematically lower than in either of the neighboring isotones (Fig. 2.6). The quadrupole moment is a direct measure of deformation, and the crossing frequency is sensitive to deformation through the position of the highly alignable quasineutrons (excited at the band crossing) relative to the Fermi level. In this mass region larger deformation removes these alignable orbitals further from the band crossing, thereby increasing $\hbar\omega_c$. In both cases the addition of an odd proton corresponds to a reduction in deformation. In contrast, the addition of a pair of protons corresponds to increased deformation!

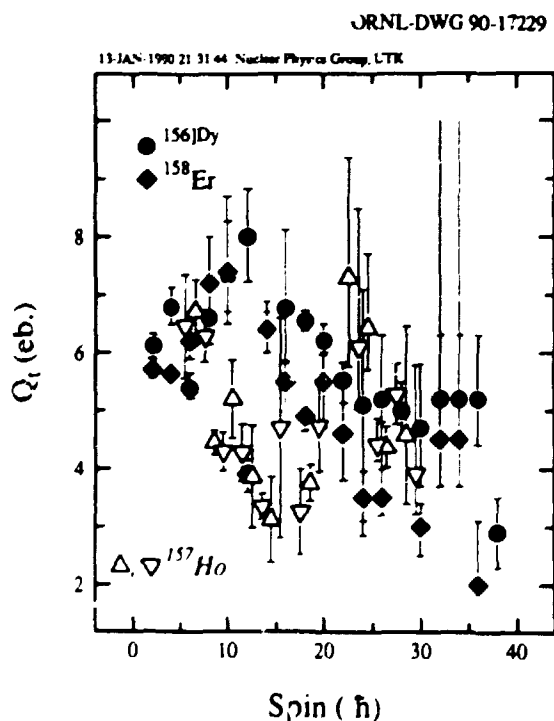


Fig. 2.5. Comparison of Q_t values extracted from lifetime measurements for the yrast decay sequences of the $N = 90$ isotones, ^{156}Dy (Ref. 3) (filled dots), ^{157}Ho (Ref. 4) (open triangles), and ^{158}Er (Refs. 5 and 6) (filled diamonds). The different orientation of the triangles denote the different signatures of the odd- Z decay sequence.

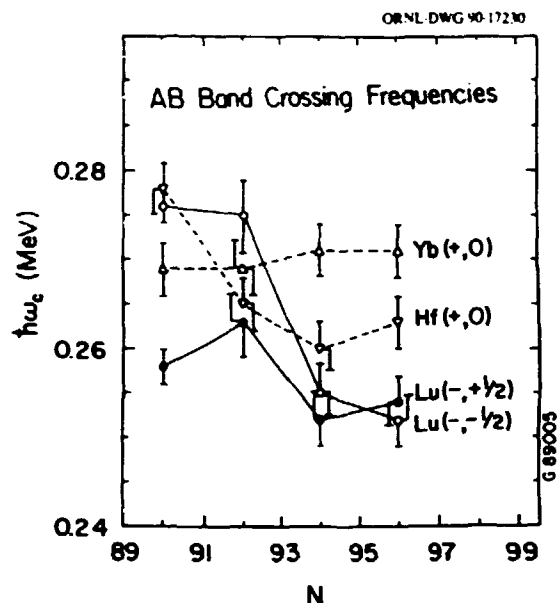


Fig. 2.6. Comparison of $\hbar\omega_c$ corresponding to the excitation of the lowest pair of quasineutrons in isotones of ^{170}Yb , ^{171}Lu , and ^{172}Hf . The experimental sources of these data are summarized in Ref. 7.

The solution to this paradox is associated with the different occupation of single-proton states when a single and a pair of protons are added to an even-even nucleus. When a single proton is added, it occupies a specific orbit with 100% probability. The unpaired proton also "blocks" the pairing contributions associated with its orbit, thereby modifying the occupation of all of the other orbits near the Fermi level. In contrast, the addition of a pair of protons produces only a minor modification in the pair correlations. The rather diffused Fermi surface simply moves sufficiently to accommodate the two additional protons. In the specific cases considered, both effects (i.e., the addition of an odd $\Omega = 7/2$ or $9/2$ $h_{11/2}$ proton and the reduced occupation of the $\Omega = 1/2$ $h_{9/2}$ proton orbital lying above the Fermi level due to reduced proton pair correlations) will reduce the quadrupole moment of the odd- Z nucleus relative to its neighboring even-even isotones.

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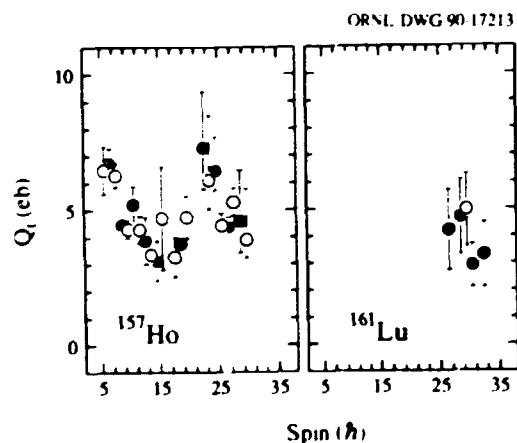
HIGH SPIN LIFETIMES IN ^{161}Lu

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High spin states of ^{161}Lu were populated using the $^{120}\text{Sn}(^{45}\text{Sc}, 4n)^{161}\text{Lu}$ reaction at a beam energy of 205 MeV with self-supporting and gold backed targets. In the backed-target experiment, the recoiling ions produced in the 1 mg/cm² tin target were slowed down and stopped in a 10 mg/cm² gold backing. A total of 120 million triple γ -ray coincidence events were collected, and Doppler broadened lineshapes were measured in the four 45° and four 135° detectors. These lineshapes are analyzed with the computer program DSAMFT developed by Bacelar and Gascon.^{4,5} The stopping power of the recoil ion with respect to both the target and the backing materials takes into account the contributions from both the electronic interaction and the nuclear scattering. The tabulated values of Ref. 6 were used for the electronic stopping power and corrected for the atomic shell structure of the stopping material.⁷ The contribution from nuclear scattering is obtained by simulating the nuclear scattering process according to a multiple Coulomb scattering formalism.⁸ In such a simulation, the Monte Carlo technique⁹ is employed to compute the velocity vector of a recoiling ion in the target and backing materials. The velocity distribution is obtained by averaging over 4000 calculated events.

The side feedings in the analysis are modeled as a rotational cascade for each level. The $J(2)$ moment of inertia and the transition quadrupole moment, Q_t , are assumed to be the same within each side feeding cascade. Both the number of levels, N , and the dynamic moment of inertia, $J(2)$, in a side feeding cascade can be varied, and it was found that $N = 4$ and $J(2) = 40 \hbar^2 \text{ MeV}^{-1}$ give the least χ^2 in the current work.

The resulting transition quadrupole moments for ^{161}Lu are plotted in Fig. 2.7 together with those for ^{157}Ho . Figure 2.7 shows that the transition quadrupole moments in ^{161}Lu are about 10% smaller than those of ^{157}Ho , the only other odd- Z $N = 90$ isotope for which lifetimes have been measured for high spin states. This difference explains about 20% of the large $B(M1)/B(E2)$ ratios¹⁰ for ^{161}Lu compared to ^{157}Ho .



12-2079 (1990) 12-18 79 The Ohio Physics Group 1278

Fig. 2.7. Transition quadrupole moment, Q_t , as a function of spin for ^{161}Lu and ^{157}Ho .

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ENHANCED B(E1)/B(E2) RATIOS IN ^{164}Yb AND THE OCTUPOLE INSTABILITY

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Earlier studies of ^{162}Er and ^{164}Yb ^{4,5} have revealed that the lowest negative-parity band, the $(\pi, \alpha) = (-, 1)$ -band, is systematically depressed about 200 keV relative to the next lowest negative-parity band, the $(-, 0)$ -band, for the complete range of known rotational frequencies. This observation together with the lack of signature splitting in the lowest negative-parity decay sequence in the neighboring odd-N isotopes suggests that the low-lying negative-parity odd-spin decay sequence is strongly coupled with the octupole configuration. To further clarify such a strong interaction between the octupole and aligned quasineutron configurations observed in the $N = 94$ erbium and ytterbium, we have extracted the B(E1)/B(E2) branching ratios from a recent experimental study of ^{164}Yb at HHIRF. Ytterbium-164 was populated using the $^{124}\text{Sn}(^{44}\text{Ca}, 4n)^{164}\text{Yb}$ reaction at an incident energy of 189 MeV. About 80×10^6 triple γ -ray coincidences were accumulated.

Table 2.1 shows the B(E1)/B(E2) ratios derived for transitions from the different levels of ^{164}Yb , and also the estimated B(E1) values. For comparison, the E1/E2 branching ratios also were extracted for $^{162,166}\text{Yb}$ and ^{164}Er , and are plotted in Fig. 2.8. Indeed, the branching ratios in ^{164}Yb are enhanced with respect to the neighboring isotopes. Furthermore, the absolute B(E1) values of ^{164}Yb shown in Table 2.1 are of the order of 10^{-3} W.u., comparable to those observed in the Ba-Sm nuclei. The enhanced octupole strength for ^{164}Yb probably is the result of the proximity of the $\Omega = 3/2$ component of the $\nu i_{13/2}$ and $\nu f_{7/2}$ states near the Fermi level for

Table 2.1. Electric dipole transition strength in ^{164}Yb .

E_γ (keV)	$I_i^\pi \rightarrow I_f^\pi$	I_γ	$\frac{B(E1)}{B(E2)}$	$\frac{B(E1)}{B(E1)^\dagger}$
			$(10^{-6} \text{ fm}^{-2})$	$(\times 10^{-3})$
324.7	$9^- \rightarrow 7^-$	<1.0	>0.06	>0.46
776.6	$9^- \rightarrow 8^+$	10.3		
401.1	$11^- \rightarrow 9^-$	4.4(2)	0.09(1)	0.72(8)
647.3	$11^- \rightarrow 10^+$	13.8(6)		
462.3	$13^- \rightarrow 11^-$	<6.6	0.15(1)	1.22(8)
533.3	$13^- \rightarrow 12^+$	9.5(5)		
514.4	$15^- \rightarrow 13^-$	16.1(9)	0.18(2)	1.49(16)
514.4	$15^- \rightarrow 13^-$	16.1(9)	0.18(2)	1.49(16)
290.9	$15^- \rightarrow 14^+$	2.6(2)		
610.3	$19^- \rightarrow 17^-$	12.1(7)	0.07(1)	0.59(8)
619.1	$19^- \rightarrow 18^+$	3.3(3)		

[†]B(E2; $2^+ \rightarrow 0^+$) for $^{164}\text{Yb} = 0.918 \text{ e}^2 \text{ b}^2$. A constant quadrupole moment was assumed although a change with spin is possible. B(E1) for $^{164}\text{Yb} = 0.0193 \text{ e}^2 \text{ b}$.

$N = 94$. However, the octupole instability in ^{164}Yb is less pronounced than for Ba-Sm nuclei [$\pi(h_{11/2} \otimes d_{5/2})$ and $\nu(i_{13/2} \otimes f_{7/2})$] and Ra-Th nuclei [$\pi(i_{13/2} \otimes f_{7/2})$ and $\nu(j_{15/2} \otimes g_{9/2})$], where at least one set of the octupole driving orbitals has $\Omega = 1/2$. These systematics indicate that the larger spatial localization of the $\Omega = 1/2$, high-j configurations probably is important in stabilizing the octupole shape.

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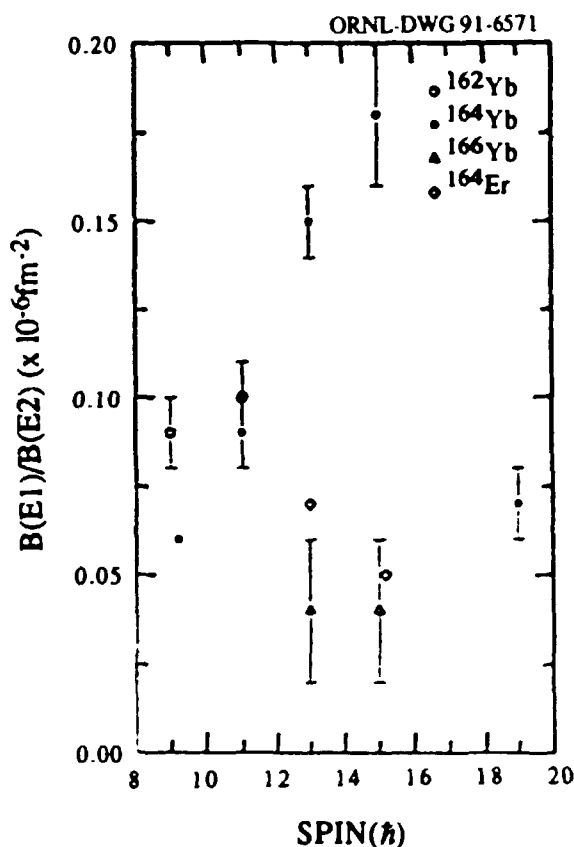


Fig. 2.8. $B(E1)/B(E2)$ branching ratios. Data are taken from Ref. 6 and the present work.

STUDY OF SPIN-TEMPERATURE EFFECTS USING ENERGY-ORDERED CONTINUUM GAMMA-RAY SPECTROSCOPY TECHNIQUE

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With the prospects of the GAMMASPHERE in mind, we have initiated a new study which extends the continuum γ -ray spectroscopy techniques to explore the differential effects of spin and temperature on such

parameters as γ strength functions, rotational-damping width, Γ_{rot} , and dynamical moment of inertia, $J(2)$. The technique revolves around ordering deexcitation γ rays of compound nuclei according to their energies on an event-by-event basis. For an ideal rigid rotor, energies of the emitted γ rays increase linearly with spin. Therefore, for a given cascade, the energy of a γ ray directly reflects its relative position (i.e., spin) in that cascade. Histogramming energies of the 1st, 2nd, ..., nth emitted γ rays will, therefore, result in a series of equally spaced δ -functions that are separated by $\Delta(E_\gamma) = 4\hbar^2/J(2)$.

However, two factors perturb this simple relationship in realistic nuclei. First, competition of the statistical transitions with the collective transitions produces exponentially-decaying wings that are superimposed on the above sharp distributions. From the slopes and intensities of these wings we can infer the cooling rate and the $E1/E2$ ratios of gamma-ray strength functions as a function of spin and temperature. A second confounding factor is due to the rotational damping width which generates finite widths for the above distributions. Conversely, the observed distribution widths are related to Γ_{rot} . Therefore, after correcting for detector response functions, the experimentally observed deviations from the ideal rigid-rotor pattern may be used to deduce important information about nuclear properties at finite temperature. This technique requires the use of 4π detector systems that detect nearly all emitted γ rays.

We have applied these ideas to the case of the well-deformed ^{170}Hf nucleus which was produced in the $^{130}\text{Te}(^{44}\text{Ca}, 4n)$ reaction at 195.5 MeV beam energy. The experimental setup consisted of the Spin Spectrometer (SS) and the ORNL Compton Suppression Spectrometer System (18 Ge). The NaI elements of the SS were used to obtain both continuum γ ray spectra and information regarding the total coincidence pulse height (H), and fold (k). Discrete γ rays emitted from the low-lying states in ^{170}Hf were used as gates to uniquely identify cascades associated with this residual nucleus. Figure 2.9 shows histograms of the energy-ordered (1st, 2nd, 3rd, 4th, 6th, and 10th) γ rays from $k = 20$ fold events. The slopes of the high-energy statistical tails of these

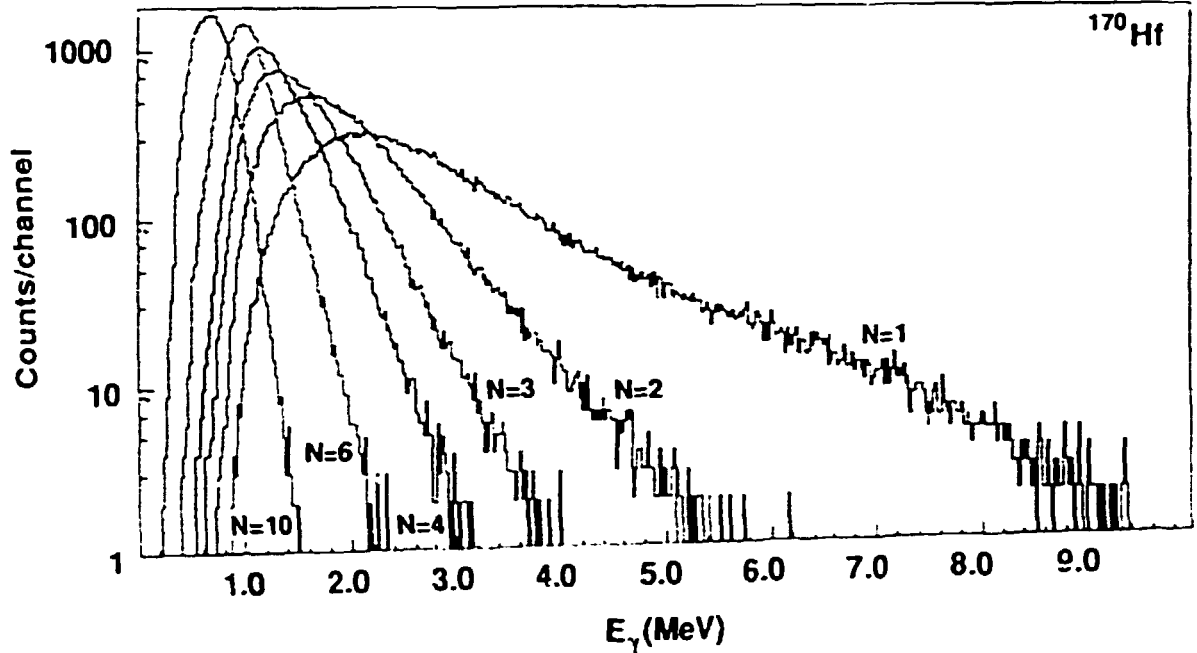


Fig. 2.9. Energy-ordered γ rays for $k = 20$ events.

spectra quickly increase as we go to the later transitions, clearly reflecting the effects of the cooling process. For $N > 5$, the distributions become nearly Gaussian, with some statistical tails. Assuming the centroids of these spectra correspond to the average γ ray energies, we extracted dynamical moments of inertia which are in good agreement with the average values obtained from the high-spin discrete band structures in this nucleus. The observed widths of these distributions are due to the spread in the γ -ray energies (i.e., damping width), statistical γ -ray tails, and detector response functions. Therefore, they represent upper limits on the Γ_{rot} values. The experimentally extracted FWHM values gradually increase with increasing γ -ray energy and reach a value of ~ 280 keV at $E_\gamma = 1.0$ MeV, and excitation energy of $U = 7.5$ MeV. The increase of the FWHM with temperature is slower than the $\sqrt{T}$ scaling. Monte Carlo simulations that account for the detector response function are under way to extract quantitative estimates of variation of Γ_{rot} with spin and temperature.

EVOLUTION OF COLLECTIVITY IN ^{172}Os

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In a previous report⁸ we presented the preliminary results from recoil-distance lifetime measurements in ^{172}Os . The data analyses have now been completed and compared with theory. Three sets of coincidence spectra from these experiments were analyzed: those from the total projected data, those generated by gating on γ rays below the transitions of interest, and those resulting from gating on the band members higher than the transition of interest. All three types of data were analyzed with the computer program LIFETIME.⁹

Average values of the transition quadrupole moments (Q_t) obtained from the analyses are plotted as a function of spin in Fig. 2.10. They show an enhancement in the collectivity in the vicinity of the 6^+ state, where the first of two anomalies in Q

occurs, while beyond the backbend there is a decrease in collectivity.

Theoretical estimates of the transition quadrupole moments involve, in principle, the microscopic initial- and final-state wave functions and are rather complicated. They can often be replaced by an approximate expression of the form

$$Q_t = \left(\frac{12}{5\pi}\right)^{1/2} (Ze)r_0^2 A^{2/3} \beta_2 \cos(30^\circ + \gamma),$$

where $r_0 = 1.2$ fm. Our potential energy surface calculations¹⁰ for ^{172}Os yield values of the deformation parameters (β_2, γ) of $(0.212, -16^\circ)$ up to $I = 18 \hbar$, where a transition to $(\beta_2, \gamma) = (0.185, -5^\circ)$ takes place. In Fig. 2.10, the dashed line, corresponding to Q_t values computed from these deformations, marks the respective trends of the shape evolution.

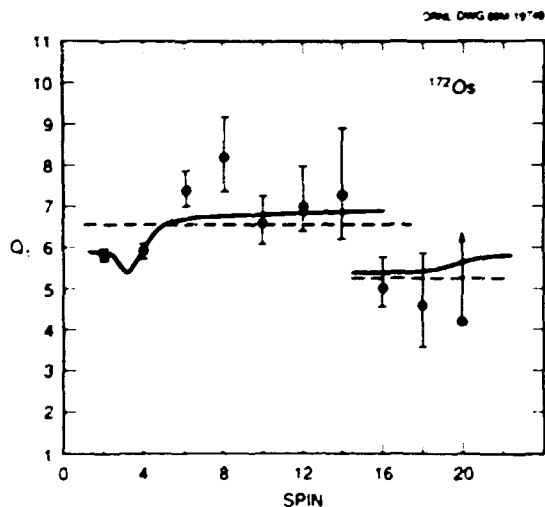


Fig. 2.10. Transition quadrupole moments (Q_t) for the yrast levels of ^{172}Os . The dashed line shows the theoretical values¹⁰ based on deformation parameters given in the text. The solid line is derived from the dynamical overlap matrix element calculations of the present work.

We have also studied the dynamical aspects of the nuclear shape by utilizing the generator coordinate method and then solving the Hill-Wheeler equation numerically in two-dimensional space. From the overlap matrix elements obtained, a new set of deformation parameters (β_2) was obtained. The

resulting Q_t values are shown as a solid line in Fig. 2.10. As seen, the trends in the data are better represented by the latter calculations. Both of these calculations invoke contributions only from $i_{13/2}$ quasineutrons.

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SIGNATURE INVERSION OF TRANSITION RATES IN ^{180}Ir

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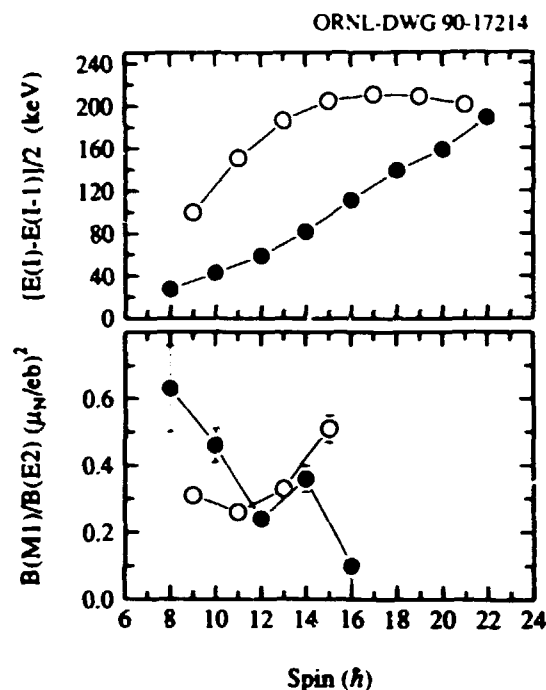
Not only does signature remain a conserved quantity in rotating deformed nuclei,² but the signature-dependent excitation energies and $\Delta I = 1$ transition rates usually are fixed by the shell model configurations that dominate the wave function of the intrinsic nuclear state.³ Due to rotationally induced Coriolis coupling, the energy of a decay sequence is signature dependent: the signature associated with $I(\text{mod } 2) = j(\text{mod } 2)$ is "favored" (occurs at a lower excitation energy) relative to that associated with $I(\text{mod } 2) = (j + 1)(\text{mod } 2)$, where j is the intrinsic

angular momentum of the unpaired nucleons. Likewise, the enhancement of $B(M1, I \rightarrow I-1)$ values for transitions decaying from "favored" to "unfavored" states is both expected and observed in many nuclei.⁴ Abnormal signature-dependent effects can appear. For example, the observed signature inversions (i.e., the exchange of favored and unfavored signatures) in both energies and $B(M1)$ values have been explained in terms of γ -vibrational excitations.⁵

Our recent study of odd-odd $^{180}\text{Ir}_{103}$ shows both signature splitting and inversion. In the decay sequence associated with the coupling of an $h_{9/2}$ proton and the two signatures of an upper-shell $i_{13/2}$ neutron, signature splittings are observed in both energies and the $B(M1)/B(E2)$ ratios (see Fig. 2.11). The unique feature in these data is the inversion at the highest spin of the $B(M1)/B(E2)$ ratio but not of the energies. In previous studies, mostly odd-A cases, the inversion of signature splitting occurs simultaneously in energies and $B(M1)/B(E2)$ ratios. Conversely, in the present case the signature inversion in $B(M1)/B(E2)$ ratios is only roughly correlated with a change of the slope of $\Delta E (= E_{\text{unfavored}} - E_{\text{favored}})$, as seen in Fig. 2.11.

It will be interesting to understand this unique signature inversion in ^{180}Ir , since recently, it has been suggested⁶ that signature inversion may be associated with proton-neutron interactions. If true, signature inversions should have different patterns in neighboring odd-odd and odd-A isotopes and isotones. In ^{181}Pt , the isotone of ^{180}Ir , a similar splitting is observed in the excitation energy, i.e., ΔE changes slope as a function of spin. However, the measured $B(M1)/B(E2)$ ratios are only available⁷ below the slope change in ΔE and no signature inversion is observed.

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Fig. 2.11. Signature-dependent energies (top) and $B(M1)/B(E2)$ ratios (bottom) as a function of spin for the sequence associated with the coupling of a $h_{9/2}$ proton and the two signatures of an upper-shell $i_{13/2}$ neutron in ^{180}Ir .

SEARCH FOR SUPERDEFORMATION IN ^{191}Tl

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High spin states in ^{191}Tl have been populated via the $^{159}\text{Tb}(^{36}\text{S},4n)$ reaction at 165 MeV, using the Holifield tandem accelerator. This reaction was selected principally because it produces the residual nuclei in a state of excitation energy and angular momentum very similar to the successful reactions in this region where discrete superdeformed bands were observed [$(E^*, l_{\text{max}}) = (24 \text{ MeV}, 50 \hbar)$]. Fission represented the main competing reaction channel in our measurement and over 100 million events were

accumulated with a minimum γ -ray fold of $K=10$, as detected by the NaI counters of the Spin Spectrometer loaded with 20 Ge detectors. A first analysis revealed a very weak signal of 6 transitions (417.2, 455.2, 493.2, 529.8, 565.6 and 599.2 keV) with a spacing of approximately 38 keV. The intensity of these transitions was estimated to be lower than 0.5% of the total $4n$ reaction channel. A second sorting of the data with $K \geq 12$ has improved the signal and suggests the presence of a seventh transition (632.9 keV). Due to the very weak intensities involved and the presence of contamination peaks, it is very difficult to invoke coincidence relationships to firmly establish the presence of this band. However, all the characteristics fit very well in the systematics of the other superdeformed bands found in the Hg-Tl-Pb region. First, the dynamical moment of inertia of this possible band in ^{191}Tl is increasing with rotational frequency at the same rate observed in the neighboring nuclei. Second, the weak intensity would also follow the trend present in the Hg nuclei, where the ^{190}Hg superdeformed band is populated at the 1% level which is lower than in the heavier isotopes. The SD bands reported in $^{193}\text{Tl}^5$ and $^{194}\text{Tl}^6$ are populated at a weaker intensity than in the Hg isotopes. Third, the lowest observed transition of 417.2 keV (which is higher than in the heavier Tl and Hg isotope) indicates a decay out of the band at higher frequency similar to ^{190}Hg with a transition of 360 keV. This last point is predicted by calculations that show a reduction of the potential depth with decreasing neutron number.

We have completed a second experiment where the residual ^{191}Tl nuclei were produced via the $^{169}\text{Tm}(^{26}\text{Mg},4n)$ reaction at 128 MeV. The decaying γ rays were detected using the Compact Ball with 20 Compton-suppressed Ge counters. The lighter ^{26}Mg beam helped to significantly reduce the fission yield and we were able to improve the statistics over the previous experiment by a factor of 5, resulting in 5.5×10^8 events. The data have been sorted into matrices and a triple sort is in progress. The possible SD signal from our earlier Spin Spectrometer measurement is being investigated in this new data set.

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A THEORETICAL INVESTIGATION OF THE PROTON $h_{9/2}$ CROSSING IN Ir-Au ISOTOPES

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There has been much debate over whether there is systematic evidence for a bandcrossing due to the alignment of $h_{9/2}$ protons. Johansson et al.³ have measured levels in ^{187}Au and attribute a sharp crossing in the $1/2[660] (\pi i_{13/2})$ band at $\hbar\omega = 0.23$ MeV to such a $\pi h_{9/2}$ bandcrossing. However, in the recently observed $\pi i_{13/2}$ bands in Ir nuclei, there are no sharp crossings but instead a gradual gain in aligned angular momentum (i) as a function of rotational frequency. The same pattern of smoothly increasing i is also present in the bands in Ir built on the $d_{5/2}$ and $h_{11/2}$ configurations, but not in the $\pi h_{9/2}$ bands which show the expected feature of a sharp neutron $i_{13/2}$ crossing at $\hbar\omega = 0.3$ MeV. The purpose of our work has been to theoretically understand the role of $\pi h_{9/2}$ alignment in these smooth alignment features in Ir nuclei.

The Fermi surface for Ir nuclei ($Z = 77$) lies in a very strategic place, just above a rather large $Z = 76$ gap in the single particle spectrum caused by upsloping $d_{5/2}$ and $h_{11/2}$ orbitals below the gap and downsloping $i_{9/2}$ above. The deformation of ^{179}Ir is therefore larger in the $\pi d_{5/2}$ and $\pi h_{11/2}$ bands ($\beta_2 = 0.26$) than in the core nucleus ^{178}Os (0.23), since a pair of protons occupies the downsloping $h_{9/2}$ orbitals and a hole is formed in the upsloping $d_{5/2}$ or $h_{11/2}$ level. These configuration-dependent deformation parameters are obtained from self-consistent Total Routhian Surface (TRS) calculations and used in the standard Woods-Saxon Cranked Shell Model code to give the predicted crossing frequency ($\hbar\omega$) and interaction strength (V_{int}) for the $\pi h_{9/2}$ crossing.

The results of these calculations are shown in Fig. 2.12 for Au and Ir isotopes. Note that the $\pi h_{9/2}$ crossing frequency and the interaction strength minimize for the Au isotopes at $A = 187$, due to the rather large β_4 value (-0.030) and γ (11°) that occur for this isotope. Even though the crossing frequency is predicted to be too large (0.30 vs. 0.23 MeV), it is impressive that the minimum value of $\hbar\omega$ and V_{int} occurs for ^{187}Au in the theory. By comparison, the $\pi h_{9/2}$ crossing in the $\pi d_{5/2}$ and $\pi h_{11/2}$ bands of Ir nuclei is predicted to occur at a higher frequency (0.35 MeV) and with much larger interaction strength (0.4 vs. 0.1 MeV). Thus, one expects in Ir nuclei a very gradual $\pi h_{9/2}$ alignment process to take place, which is compatible with what is observed experimentally in the frequency range of 0.15 to 0.30 MeV/ $\hbar$.⁴

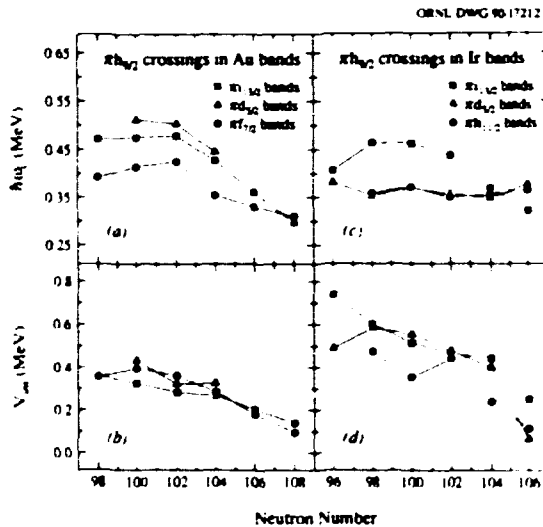


Fig. 2.12. Calculated $\pi h_{9/2}$ crossing frequencies (a,c) and interaction strength (b,d) as a function of neutron number for several bands in odd-A Au and Ir isotopes.

Another plausible explanation for the observed gradual rise in i values in ^{179}Ir is that there seems to have been a stretching in the shape due to a frequency-dependent scattering of a pair of protons from the upsloping to the downsloping orbitals. However, the downsloping orbital, mainly $h_{9/2}$, is blocked in ^{179}Ir , so that the possibility of pair scattering is

highly reduced. Therefore the stretching should not play a significant role in causing the gradual rise in i values in Ir nuclei. But the stretching may be larger in Re isotopes due to the existence of unblocked downsloping orbitals.⁴

1. Partial support provided by Joint Institute for Heavy Ion Research, ORNL and the University of Tennessee, Knoxville.

2. University of Tennessee, Knoxville.

3. J. K. Johansson et al., *Phys. Rev. C* **40**, 132 (1989).

4. H.-Q. Jin et al., *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1988*, ORNL-6508, p. 80; to be published.

"IDENTICAL" ROTATIONAL BANDS IN NORMALLY-DEFORMED NUCLEI

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Recently, superdeformed decay sequences have been observed in neighboring odd-A and even-even isotopes identical in energy by 1-2 parts per thousand.³ The decoupling of these bands have been explained⁴ in terms of pseudo SU(3) symmetry; however, the "identical" moments of inertia of these bands which this data implies remain a mystery.

It is well known for normally-deformed nuclei that the addition of an odd nucleon *usually* produces a major reduction of the moment of inertia, a result of reduced pair correlations in the odd-A nucleus. The occupation of an odd orbital "blocks" the contributions of the occupied configuration to pair correlations. However, Figure 2.13 demonstrates that under certain conditions the moment of inertia is not reduced in normally deformed odd-A nuclei relative to their even-even neighbors - i.e., sequences in normally deformed neighboring isotones also can be "identical." In fact, the reduction of the moment of inertia for the occupation of the $1/2^+[411]$ proton orbital (a negatively-decoupled orbital, i.e., $a = -1$, in the pseudospin limit) is anticorrelated with the excitations of this orbital relative to the Fermi level (expressed in the plot as the excitation energy of the bandhead). When a configuration is far from the Fermi level, it does not contribute to pair

correlations, so the pairing contributions to the moment of inertia are unaffected by its occupation.

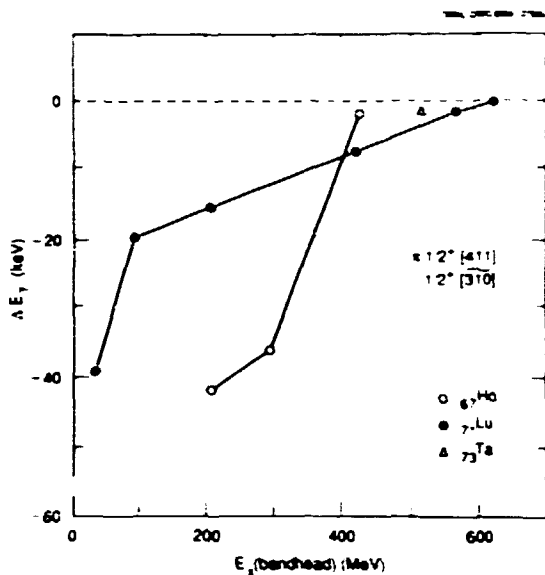


Fig. 2.13. Correlation between ΔE_γ , the difference in γ -ray energy for transitions in neighboring odd-Z and even-even isotones, for the $\pi 1/2^+[411]$ configuration in Ho, Lu, and Ta isotopes and the excitation energy of the bandhead of this configuration in the odd-Z isotones. $\Delta E_\gamma \equiv E_\gamma(Z) - 0.5[E_\gamma(Z-1) + E_\gamma(Z+1)]$, where Z is odd. This comparison is for an average of the $5/2^+ \rightarrow 1/2^+$ and the $7/2^+ \rightarrow 3/2^+$ transitions in the odd-Z nuclei with an average of the $2^+ \rightarrow 0^+$ and the $4^+ \rightarrow 2^+$ transitions in the even-even isotones - see Ref. 4.

The odd nucleon also can influence the nuclear shape directly. ΔE_γ is expected, and indeed is observed, to be anticorrelated with j_1 , the component of the intrinsic angular momentum on the rotational axis. Microscopically, the kinetic moment of inertia is given⁵ by $\mathcal{J}^{(1)} = \Sigma j_j/\omega$. The j_1 associated with the $1/2^+[411]$ configuration (dominately based on the $2d_{3/2}$ and $3s_{1/2}$ shell-model states) is small. Therefore, when the effects of pair correlations are minimized, "identical" bands in neighboring isotones is not so anomalous, especially when the first-order Coriolis effects on j_1 are removed by averaging the E_γ values for the two signatures in the odd-Z isotope.

1. University of Tennessee, Knoxville.
2. Warsaw University of Technology, Warsaw, Poland.
3. T. Byrski et al., *Phys. Rev. Lett.* **64**, 1650 (1990).
4. W. Nazarewicz, P. J. Twin, P. Fallon, and J. D. Garrett, *ibid.*, p. 1654.
5. H. Sagawa and Th. Døssing, *Phys. Lett.* **96B**, 238 (1980).

EMPIRICAL ESTIMATES OF THE PROTON-NEUTRON INTERACTION AND DIABOLICAL POINTS¹

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The use of constant- N contours in the (ω, λ) plane is demonstrated both for establishing diabolical points and for studying regularities and fluctuations in the spectrum of single-particle states. Likewise the average properties and fluctuations of empirical proton-neutron interactions, obtained from double differentials of the total energy with respect to N and Z , are discussed for the ground states of all even-even nuclei with $N > 40$ and as a function of the rotational frequency for the lowest even-spin, positive-parity decay sequence of deformed rare earth nuclei.

1. Abstract of paper to be published in *Nuclear Physics*.
2. Center of Theoretical Physics, CCAST (World Laboratory), P.R. China.
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9. Argonne National Laboratory, Argonne, IL.

NUCLEAR STRUCTURE STUDIES VIA RADIOACTIVE DECAY

SUPERALLOWED $^{26}\text{Al}^m(\beta^+ + \text{EC})^{26}\text{Mg}$ DECAY¹

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The reaction energies of $^{25}\text{Mg}(n, \gamma)^{26}\text{Mg}$ and $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}^m$ have been measured as $Q = 11093.24 \pm 6$ and 6078.09 ± 8 keV, respectively, which yields $Q = 4232.81 \pm 10$ keV for the $^{26}\text{Al}^m(\beta^+ + \text{EC})^{26}\text{Mg}$ decay energy. By combining it with the known $^{26}\text{Al}^m$ half-life and by applying electro-magnetic corrections one obtains $T_1 = 3073.5 \pm 18$ s for this superallowed $0^+ \rightarrow 0^+$ decay in good agreement with the value for the ^{14}O "standard" $0^+ \rightarrow 0^+$ decay $T_1 = 3075.8 \pm 16$ s, thus resolving a long-standing discrepancy.

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EMPIRICAL ESTIMATES OF PROTON-NEUTRON RESIDUAL INTERACTIONS IN ^{78}Rb ¹

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With the use of the University Isotope Separator at Oak Ridge (UNISOR) facility on-line at HHIRF, an experiment was performed for the first time to study the isomeric decay of the beta decaying 5.74-minute isomer in ^{78}Rb . The ^{78}Rb nuclei were produced in 110-MeV ^{28}Si bombardment of an Au

coated natural Fe target and, following mass separation, were assayed with Si(Li) and intrinsic Ge detectors. The γ -ray and electron singles, as well as γ -electron coincidence data were accumulated.

In the γ -ray singles spectrum, we observed the strong 103.0-keV and the weaker 46.8-keV γ rays which are known⁸ to follow the decay of the 5.74-minute isomer in ^{78}Rb . In the electron singles spectrum, we observed the K and L+M conversion lines of these transitions and also of a newly identified 64.4-keV transition. The conversion electrons of the 64.4-keV γ transition were also seen in coincidence with the 46.8-keV γ transition (see Fig. 2.14). The L+M to K conversion coefficient ratio is measured from the coincidence data to be 0.367 ± 0.030 which is consistent only with the M3 multipolarity. From our singles spectra, the K conversion coefficients of the 46.8- and 103.0-keV transitions were determined to be 0.76 ± 0.11 and 0.10 ± 0.02 , which are in excellent agreement with E1 and M1 multipolarities, respectively.

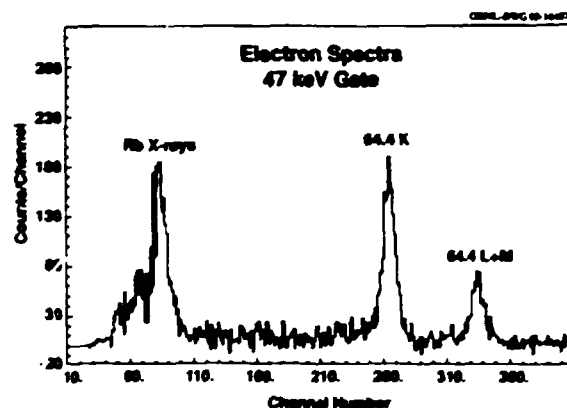


Fig. 2.14. Electron spectrum in coincidence with the 46.8-keV γ ray.

We also identified another new transition, the L+M conversion electron peak of an 8.6-keV transition, in coincidence with the 103.0-keV γ transition (see Fig. 2.15). These parallel cascades place the 5.74-min isomer in ^{78}Rb at an excitation energy of 111.2 keV above the $0^{(+)}$ ground state.

Figure 2.16 shows the ^{78}Rb level scheme constructed for the 5.74-min isomer. The E3 multipolarity for the 8.6-keV transition is deduced from the decay scheme.

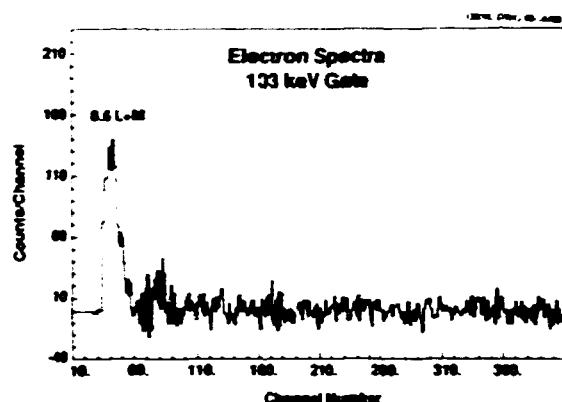


Fig. 2.15. Electron spectrum in coincidence with the 103.0-keV γ ray.

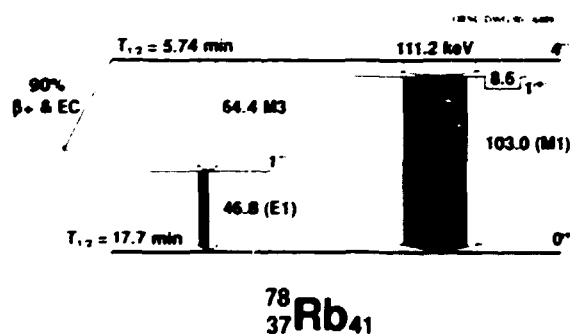


Fig. 2.16. Isomeric decay scheme for the 5.74 min ^{78}Rb .

These results, along with those for the neighboring odd-A nuclei will be used to determine empirically the proton-neutron residual interaction for ^{78}Rb .

1. Summary of a paper to be submitted to *Physical Review C*.

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5. Georgia Institute of Technology, Atlanta.

6. UNISOR, Oak Ridge Associated Universities.

7. Vanderbilt University, Nashville.

8. G. Bavaria et al., *Z. Phys. A* 302, 329 (1981).

SINGLE-PARTICLE STATES NEAR THE PROTON DRIP LINE

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With the use of the OASIS separator facility, on-line at the Lawrence Berkeley Laboratory SuperHILAC, we have investigated the decay properties of numerous short-lived neutron-deficient rare earth nuclei with $65 \leq Z \leq 71$. Part of the overall investigation has dealt with the study of low-lying states in isotopes near the 82-neutron shell. These levels are relatively pure single-particle states; as such, their properties can be compared with predictions of various shell-model calculations. Isotopes in this mass region that are close to the $Z = 64$ subshell are of particular interest because they provide information on the underlying spherical proton structure in nuclei located halfway between the major $Z = 50$ and $Z = 82$ closed shells. Earlier we presented³ systematics of protons in odd- Z , $N = 82$ nuclei and of neutron states in even- Z , $N = 81$ nuclei, together with results of spherical Hartree-Fock-Bogoliubov calculations. We have now extended this structure information to nuclei with higher atomic and lower neutron numbers.

In Fig. 2.17 we show systematics for the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ neutron-hole states in Sm, Gd, Dy, and Er nuclei with $N = 77, 79$, and 81. (Excitation energies for the $d_{3/2}$ levels in ^{145}Dy and ^{147}Er and the $h_{11/2}$ level in ^{145}Dy were determined in our investigation of the ^{145}Ho and ^{147}Tm β -decay schemes.) The dramatic minimum for the $h_{11/2}$ level energy at $N = 79$ may signal a change in deformation near this neutron number. We should also add that the HFB calculations³ do not reproduce the excitation

energies of the $h_{11/2}$ level for $N = 81$ nuclei. This energy, which is 242 keV in ^{131}Sn , increases to a value of 754 keV in ^{139}Ce , and then remains the same in isotopes with higher Z values. The calculations, on the other hand, predict a steady drop in excitation energy as Z increases after the maximum is reached in ^{139}Ce .

level is the ground state in Tb nuclei, the $h_{11/2}$ level, which is isomeric for $Z \leq 65$, becomes the ground state in Ho and Tm isotopes.

1. Eastern Kentucky University, Richmond.
2. Lawrence Berkeley Laboratory, Berkeley.
3. K. S. Toth et al., *Phys. Rev. C* 32, 342 (1985).

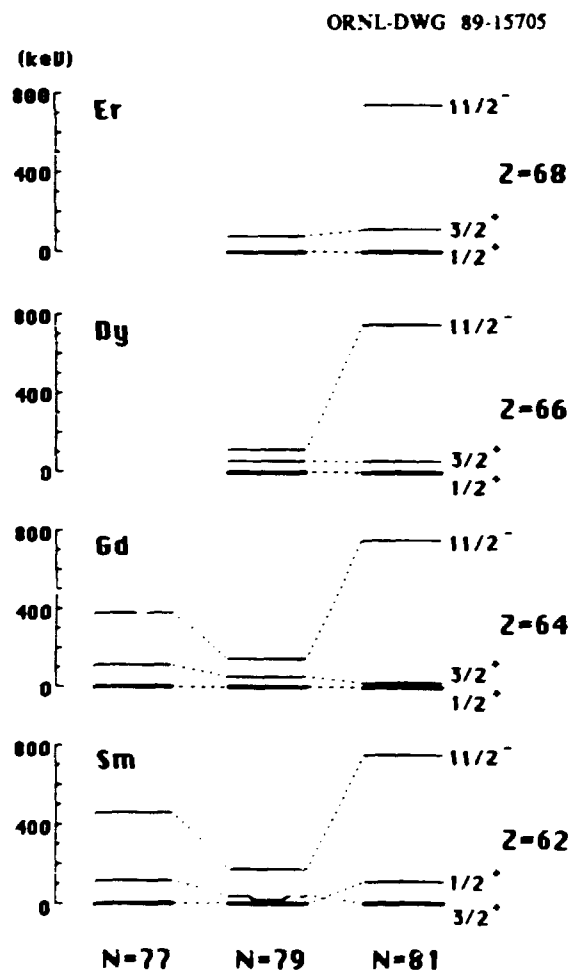


Fig. 2.17. Neutron-hole states in nuclei with $N = 77, 79$, and 81 .

We have also obtained information concerning the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, $g_{7/2}$, and $h_{11/2}$ proton states in ^{145}Tb , ^{147}Ho , ^{151}Tm , ^{151}Ho , and ^{153}Tm . These new results show that the single-proton level energies continue to follow the established trend,³ i.e., as the atomic number increases the gap between the $d_{5/2}$ and $d_{3/2}$ orbitals increases while the one separating the $d_{3/2}$ and $s_{1/2}$ orbitals decreases. Also, while the $s_{1/2}$

SINGLE-PARTICLE STATES IN ^{151}Tm AND ^{151}Er : SYSTEMATICS OF NEUTRON STATES IN $N = 83$ NUCLEI¹

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With the use of mass-separated sources, the β -decay properties of ^{151}Yb and ^{151}Tm were investigated. The $h_{11/2}$, $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ single-proton states in ^{151}Tm and the $f_{7/2}$, $h_{9/2}$, $p_{3/2}$, $i_{13/2}$, and probably the $p_{1/2}$ single-neutron states in ^{151}Er were identified. Systematics of neutron states in even- Z $N = 83$ isotones are compared with predictions of spherical Hartree-Fock-Bogoliubov calculations.

1. Abstract of published paper: *Phys. Rev. C* 41, 1126 (1990).
2. Tulane University, New Orleans, Louisiana.
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IDENTIFICATION OF THE ^{155}Tm $s_{1/2}$ ISOMER AND OF THE ^{155}Yb β -DECAY BRANCH

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The decay properties of ^{155}Yb and ^{155}Tm and of the α -decay daughters ^{151}Er and ^{151}Ho were investigated following the on-line mass separation of $A = 155$ nuclides produced in ^{64}Zn irradiations of ^{95}Mo . Figure 2.18 summarizes the α -particle and $(\text{EC} + \beta^+)$ decay chains of interest to this study. It is part of our overall investigation of nuclei in the

82-neutron region of the periodic chart, with our more recent experiments involving isotopes located on the heavier side of the $N = 82$ closed shell.

A self-supported metallic foil, 2.07-mg/cm^2 in thickness, of ^{95}Mo (enriched to 98.8%) was bombarded with 291-MeV ^{64}Zn ions extracted from the Lawrence Berkeley Laboratory SuperHILAC. The ^{64}Zn energy at the midpoint of the ^{95}Mo foil was calculated to be 273 MeV. After mass separation the $A = 155$ products were transported ionoptically to a fast cycling tape system and positioned between an array of detectors suitable for particle and γ -ray assay. In the course of this experiment the β -decay branch of ^{155}Yb was identified by observing β -delayed γ rays

and Tm K X rays, and the existence in ^{155}Tm of an $s_{1/2}$ isomer ($T_{1/2} = 44 \pm 4$ s), in addition to the $h_{11/2}$ ground state, ($T_{1/2} = 21.6 \pm 0.2$ s), was established. Schemes for the β decays of ^{155}Yb , ^{155}Tm , and ^{151}Er are proposed. New information on ^{151}Er decay establishes the $s_{1/2}$ isomer in ^{151}Ho to be 41.1 ± 0.2 keV above the $h_{11/2}$ ground state. Also, branching ratios of 90 ± 5 , 30 ± 10 , and $85 \pm 10\%$ were determined for the α decays of ^{155}Yb , ^{151}Ho , and $^{151}\text{Ho}^m$, respectively.

1. Lawrence Berkeley Laboratory, Berkeley.
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3. Eastern Kentucky University, Richmond.

ORNL-DWG 88-15704R

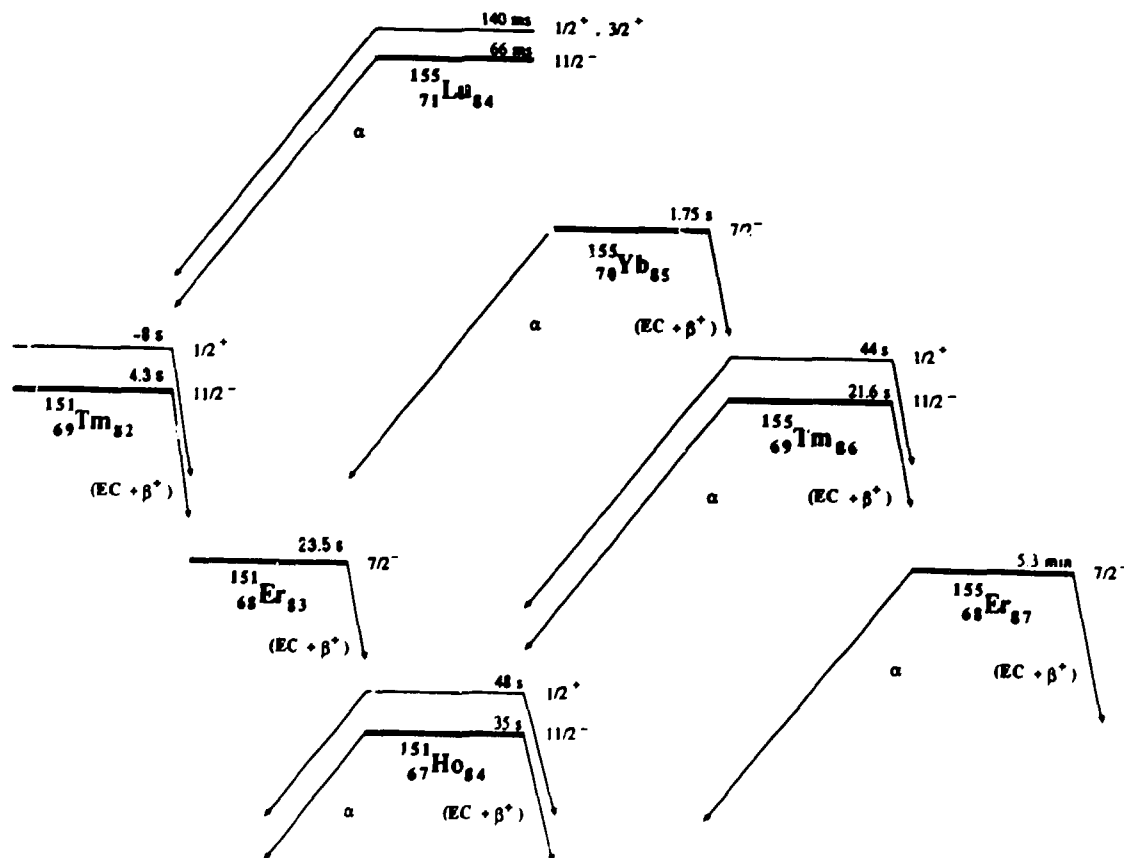


Fig. 2.18. Schematic summary of the $A = 155$ and $A = 151$ decay chains.

ALPHA-DECAYING LOW-SPIN LEVELS IN ^{157}Lu AND ^{155}Lu

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We have investigated the α -particle decays of ^{157}Lu and ^{155}Lu by using the OASIS isotope separator, on-line at the Lawrence Berkeley Laboratory SuperHILAC.

Figure 2.19 shows the α -particle spectrum that we measured at $A = 157$. In addition to α particles emitted by ^{149}Tb , ^{153}Ho , ^{157}Yb , ^{153}Er , ^{153}Tm , and the known (Ref. 2) ^{157}Lu , $h_{11/2}$, state [4988(5) keV], we observe a new α group, 4924(20) keV, which we assign to the decay of a previously unreported low-spin ($1/2^+, 3/2^+$) level in ^{157}Lu . Our data indicate that the half-life of this state is 5.7(2) sec rather than the 4.8(2)-sec value of the $h_{11/2}$ level. Information on the β decay properties of the two ^{157}Lu states has hitherto not been available.² We observe numerous γ rays following ^{157}Lu β decay and have constructed a scheme for ^{157}Yb states that are populated by the high-spin ^{157}Lu level. Based on these α - and β -decay data we deduce an α -branching ratio of 18(5)% for this ^{157}Lu state. This value disagrees with the ratio of 6(2)% reported by Hofmann et al.³ Because of the smaller production cross section for the low-spin state, a β -decay scheme could not be constructed for it, and its α -branching ratio could not be determined.

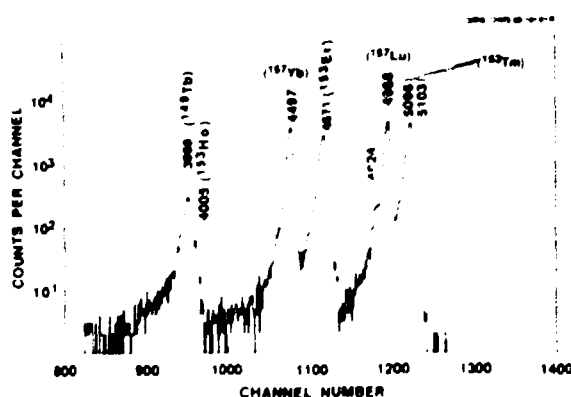


Fig. 2.19. Alpha-particle spectrum measured at $A = 157$. Energies are expressed in keV. The 4924-keV α group is assigned to the decay of a previously unobserved low-spin level in ^{157}Lu .

In the $A = 155$ spectrum we observed two groups that belong to ^{155}Lu α -particle decay, i.e., 5579(5) and 5648(5) keV. The higher energy group has been known⁴ since 1965 and is presumed to follow the α decay of the 66-ms $h_{11/2}$ state; this level has an α decay branch³ of ~79%. Recently, Hofmann et al.⁵ reported α -particle decay from a second low-lying ^{155}Lu state. Our observation of the 5579-keV peak confirms the existence of this new α -emitting level which we believe is either the $s_{1/2}$ or $d_{3/2}$ single-proton state. No half-life for it was reported by Hofmann et al.⁵; we measure a value of 140(20) ms. As in the case of ^{157}Lu , an α decay branch for this low-spin level could not be determined.

Reduced widths of 0.074 and 0.197 MeV were calculated for the 5648-keV (^{155}Lu) and 4988-keV (^{157}Lu) α transitions. Since these values are comparable to those of neighboring, $N = 84$ and $N = 86$, even-even nuclei, respectively, the α transitions are unhindered and most probably connect the ^{155}Lu and ^{157}Lu $\pi h_{11/2}$ states with the corresponding $\pi h_{11/2}$ ground states in ^{151}Tm and ^{153}Tm . It would be of interest to determine the α -branching ratios of the low-spin α groups because their decay rates could indicate whether these levels in ^{155}Lu and ^{157}Lu are $s_{1/2}$ or $d_{3/2}$ proton states.

1. Lawrence Berkeley Laboratory, Berkeley.
2. R. G. Helmer, *Nucl. Data Sheets* 55, 71 (1988).
3. S. Hofmann et al., *Z. Phys.* A291, 53 (1979).
4. R. D. Macfarlane, *Phys. Rev.* 137, B1448 (1965).
5. S. Hofmann et al., *Z. Phys.* A333, 107 (1989).

IDENTIFICATION OF ^{186}Au α ACTIVITY¹

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With the use of an on-line isotope separator, the α activity of ^{186}Au was identified for the first time. Only one α group ($E_\alpha = 4653 \pm 15$ keV) was observed. This transition was found not to be in coincidence with γ rays so that it probably proceeds

either to the ^{182}Ir ground state or to a low-lying level whose deexciting γ rays could not be detected. The α -decay branching was determined to be $(8 \pm 2) \times 10^{-4}\%$ from which a hindrance factor of 1.9 ± 0.9 was deduced. The 4653-keV α transition must therefore connect the 3^{-} ^{186}Au ground state with a ^{182}Ir level with the same spin and configuration.

1. Abstract of published paper: *Phys. Rev. C* 42, 1130 (1990).
2. Adjunct staff member, University of Tennessee, Knoxville.
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HEAVY-ION REACTION MECHANISM STUDIES, FUSION AND FISSION

OBSERVATION OF ENTRANCE CHANNEL EFFECTS IN COMPOUND NUCLEUS FORMATION WITH HIGH ENERGY γ RAYS

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F. E. Bertrand, C. Baktash, M. L. Halbert,
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D. W. Stracener,³ and W. Spang⁴*

We have investigated entrance channel effects in the decay of excited ^{160}Er and ^{164}Yb by measuring high energy (5-25 MeV) γ -ray spectra. Gamma rays from the decay of the giant dipole resonance (GDR) built on highly excited states provide a good probe to study these effects, as they are emitted in the early stages of the reaction.

Erbium-160 was formed at an excitation energy of 53 MeV using the reactions: $^{16}\text{O} + ^{144}\text{Nd}$ and $^{64}\text{Ni} + ^{96}\text{Zr}$. ^{164}Yb ($E^* = 49$ MeV) was formed with $^{16}\text{O} + ^{148}\text{Sm}$ and $^{64}\text{Ni} + ^{100}\text{Mo}$. The high energy γ rays were detected using 4 close-packed arrays consisting of 19 hexagonal BaF_2 (6.5 cm face to face, 20 cm long) scintillators each. In addition, the total γ -ray multiplicity was measured with the Spin Spectrometer.

Figure 2.20 shows the fold-gated γ -ray spectra for the four reactions [^{160}Er (a), ^{164}Yb (b)]. They are normalized between 8 and 9 MeV. The ^{16}O reactions show the typical GDR bump at 13 MeV as expected.

The solid lines in Fig. 2.20 are statistical model calculations using the computer code CASCADE. Only the decay of the angular momentum population between 15 and 30 $\hbar$ was calculated, matching the fold condition in the experimental data. The extracted GDR parameters ($E_1 = 12.4$ MeV, $\Gamma_1 = 4.9$ MeV, $E_2 = 15.7$ MeV, $\Gamma_2 = 7.2$ MeV for ^{160}Er and $E_1 = 12.0$ MeV, $\Gamma_1 = 5.3$ MeV, $E_2 = 16.2$ MeV, $\Gamma_2 = 7.2$ MeV for ^{164}Yb) are in general agreement with previous GDR experiments in this mass region.

In the compound nucleus decay formed with ^{64}Ni , however, the GDR seems to be almost completely absent. It is obvious that the ^{64}Ni data cannot be described with reasonable changes of the statistical model parameters for a compound nucleus decay. The ^{64}Ni induced γ -ray spectra therefore suggest some loss of energy by the composite system before it is fully equilibrated. More detailed calculations, including possible decay mechanisms before/during the shape equilibration of the fusing system, are necessary in order to explain these entrance channel effects.

1. Partial support from the Joint Institute for Heavy Ion Research, ORNL.
2. Personnel Division, ORNL.
3. Washington University, St. Louis, MO.
4. Institut für Kernphysik, Jülich, Germany.

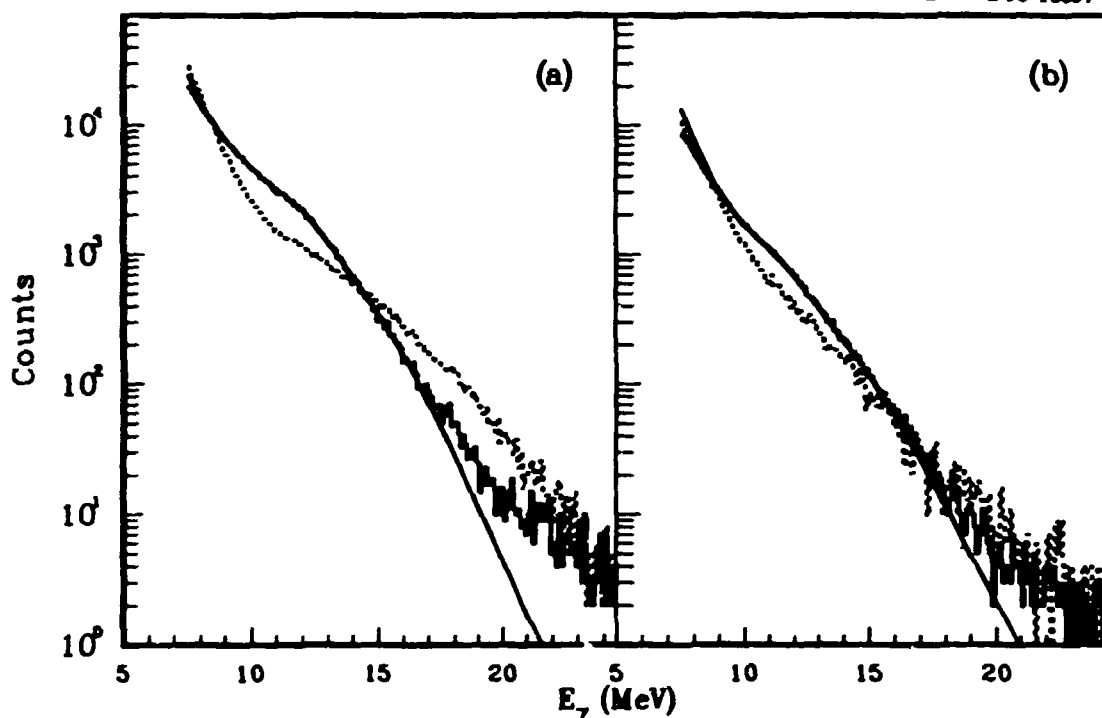


Fig. 2.20. Experimental γ -ray spectra from the decay of ^{160}Er (a) and ^{164}Yb (b). The solid histogram corresponds to the ^{16}O induced and the dashed histogram to the ^{64}Ni induced reactions. The solid curves are fits from statistical model calculations.

STUDY OF ENTRANCE CHANNEL EFFECT IN $^{31}\text{P} + ^{16}\text{O}$ VS $^{35}\text{Cl} + ^{12}\text{C}$ REACTIONS

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Backward-angle measurements of strongly damped reaction products from the $^{28}\text{Si} + ^{12}\text{C}$ (Ref. 4), $^{20}\text{Ne} + ^{12}\text{C}$ (Refs. 5 and 6), and $^{24}\text{Mg} + ^{16}\text{O}$ (Ref. 7) reactions have indicated the formation of a long-lived orbiting complex. One of the criterions to distinguish between compound nucleus and orbiting reactions should be the entrance channel dependence of back-angle yields. If a compound nucleus reaction mechanism is dominant, then the relative yields should be independent of how it is formed. If the orbiting process is dominant, then the system should

tend to break apart into the entrance channel system much more frequently than if the compound nucleus process dominates. A strong entrance channel dependence of back-angle yields was observed by comparing⁷ back-angle oxygen and carbon yields from $^{28}\text{Si} + ^{12}\text{C}$ and $^{24}\text{Mg} + ^{16}\text{O}$ reactions, as shown in Fig. 2.21. We recently performed an experiment at HHIRF to study $^{31}\text{P} + ^{16}\text{O}$ and $^{35}\text{Cl} + ^{12}\text{C}$ reactions and find out whether entrance channel effects exist in these light heavy-ion reactions in general. Backward angle yields of oxygen and carbon particles from the $^{35}\text{Cl} + ^{12}\text{C}$ reaction at $E(^{35}\text{Cl}) = 180$ MeV were measured⁸ previously. We measured back-angle yields of oxygen and carbon particles for the $^{31}\text{P} + ^{16}\text{O}$ reaction at $E(^{31}\text{P}) = 135.6$ MeV and compared with data⁸ for the $^{35}\text{Cl} + ^{12}\text{C}$ reaction. In both cases, the same ^{47}V compound nucleus is formed at

an excitation energy of 59.1 MeV and $\ell_{\text{crit}} = (27-28)\hbar$ for both the systems.

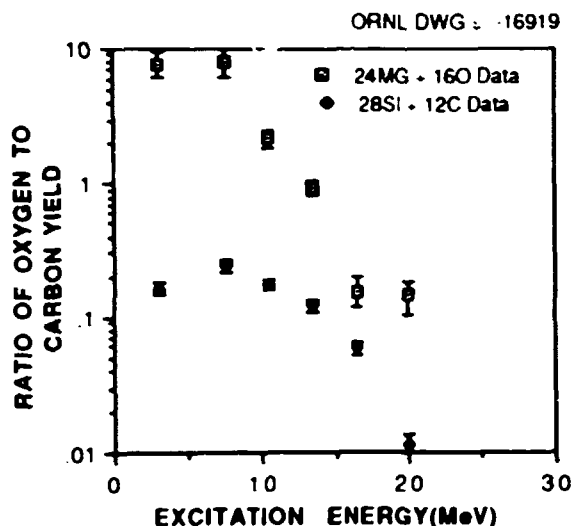


Fig. 2.21. Ratio of yields of oxygen to carbon as a function of exit channel excitation energy for $^{28}\text{Si} + ^{12}\text{C}$ and $^{24}\text{Mg} + ^{16}\text{O}$ systems.

We used a ^{16}O supersonic gas jet target and a 10 pna ^{31}P beam at $E(^{31}\text{P}) = 135.6$ MeV from the HHIRF tandem accelerator. The experiment was performed by using a hybrid ionization chamber and focal plane detector in the Enge spectrograph. The back-angle yields of oxygen and carbon particles were measured and the comparison with data for the $^{35}\text{Cl} + ^{12}\text{C}$ system is shown in Fig. 2.22. We do not see any significant entrance channel effect compared to what has been seen for the $^{28}\text{Si} + ^{12}\text{C}$ system. It appears that the entrance channel effect is dominant in systems where strong heavy-ion resonances have been seen. In the future, it would be very interesting to study the correlations between orbiting and heavy-ion resonances.

1. Partial support from the Joint Institute of Heavy Ion Research, ORNL.

2. Yale University, New Haven, CT.

3. CRN, Strasbourg, France.

4. D. Shapira et al., *Phys. Lett. B* 114, 111 (1982).

5. D. Shapira et al., *Phys. Rev. C* 26, 2470 (1982).

6. D. Shapira et al., *Phys. Rev. Lett.*, 48, 1781 (1979).

7. A. Ray et al., *Phys. Rev. C* 31, 1573 (1985).

8. C. Beck et al., *Z. Phys. A* 334, 521 (1989).

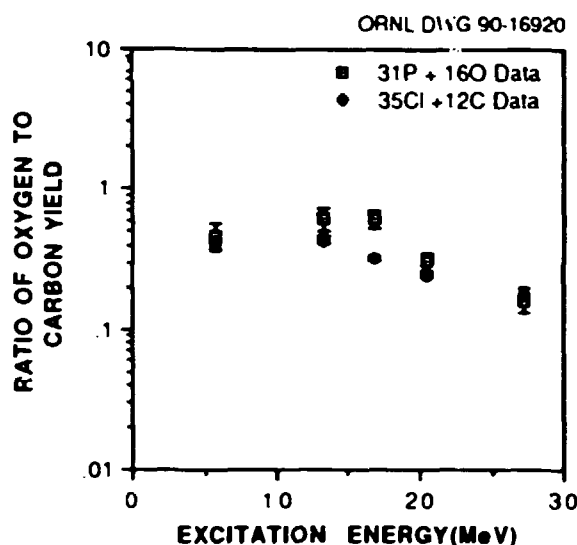


Fig. 2.22. Ratio of yields of oxygen to carbon as a function of exit channel excitation energy for $^{31}\text{P} + ^{16}\text{O}$ and $^{35}\text{Cl} + ^{12}\text{C}$ systems.

THERMAL AND ANGULAR MOMENTUM EFFECTS IN THE GIANT-DIPOLE-RESONANCE DECAY OF HOT RARE-EARTH NUCLEI¹

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D. W. Stracener²

Recoil- γ coincidences have been measured in the reaction $^{16}\text{O} + ^{159}\text{Tb}$ at beam energies of 300 and 400 MeV. In the γ -ray spectra corresponding to excitation energies above 140 MeV a split giant dipole resonance is observed with widths substantially smaller than found at lower excitation energy. The possible influence of excitation energy and angular momentum on this effect is discussed. The intensity ratio of the two dipole resonance components is found to change with excitation energy, indicating a transition of the nuclear shape from prolate towards oblate.

1. Abstract of published paper: *Phys. Rev. Lett.* **64**, 1999 (1990).
2. Institut für Kernphysik, Jülich, Germany.
3. Washington University, St. Louis.

FISSION-GIANT DIPOLE γ -RAY COINCIDENCES IN ^{175}Ta

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The γ -ray decay of the giant dipole resonance (GDR) built on highly excited states is sensitive to the nuclear shape and several experiments have been performed to study deformation effects at high spins and excitation energies.⁴ Coincidence measurements of high energy γ rays with fission fragments can be used to select only the highest spins of a given compound nucleus population.⁵ Recent observations of fission hindrance in γ -ray decay experiments preceding fission⁶ open up the additional opportunity to study dissipation effects of the fission process with γ -fission coincidence measurements.

We measured the γ -ray decay in coincidence with fission fragments following the reaction $^{16}\text{O} + ^{175}\text{Tb} \rightarrow ^{175}\text{Ta}$ at 160 MeV and 216 MeV. Four close-packed arrays of 19 BaF_2 detectors each measured the γ rays, and the fission fragments were detected in two PPAC's, which discriminated between quasielastic scattering, evaporation residues, and fission fragments.

Figure 2.23 demonstrates the spin selectivity of γ -fission coincidence measurements. It shows the spin distribution for the 160-MeV data where populations leading to evaporation residues and to fission are shown as dotted and dash-dotted lines, respectively. Figure 2.24 shows the difference between the γ -ray spectrum in coincidence with evaporation residues corresponding to spins of $< \sim 55$ (top) and the γ -ray spectrum in coincidence with fission fragments ($> \sim 55$, bottom) for the 160 MeV data.

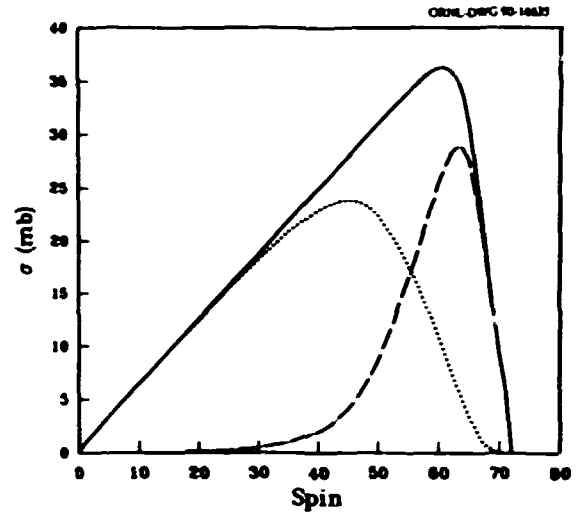


Fig. 2.23. Spin distributions for $E_{\text{beam}} = 160$ MeV: total fusion (solid), evaporation residues (dotted), and fission (dash-dotted).

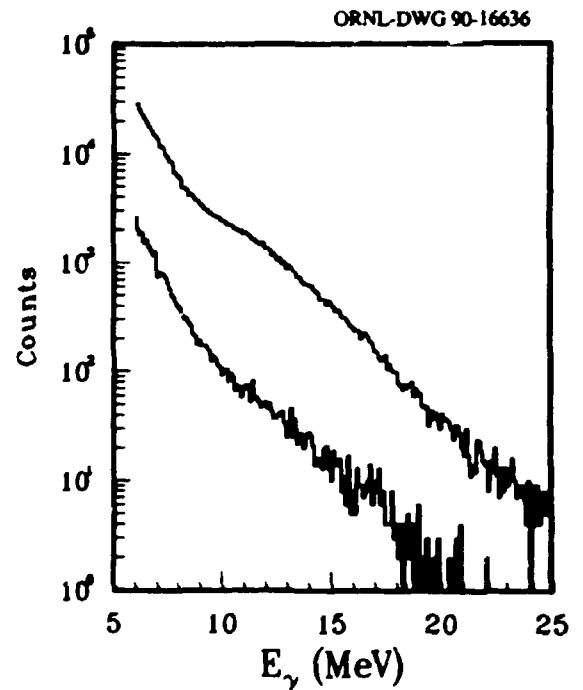


Fig. 2.24. Experimental γ -ray spectra from the decay of ^{175}Ta ($E_{\text{beam}} = 160$ MeV) in coincidence with evaporation residues (top) and fission fragments (bottom).

Preliminary statistical model calculations indicate that a large splitting of the two GDR components is required in order to fit the γ -fission coincidence data, corresponding to a large deformation of the excited high-spin states. In addition, the contribution of γ rays preceding fission have to be enhanced relative to the γ rays from the fission fragments. This shows the influence of dissipation slowing down the fission process in this reaction. The qualitative analysis of the data is currently in progress.

1. Partial support from Joint Institute for Heavy Ion Research, ORNL.
2. Washington University, St. Louis, MO.
3. Institut für Kernphysik, Jülich, Germany.
4. K. A. Snover, *Ann. Rev. Nucl. Part. Sci.* **36**, 545 (1986).
5. R. Butsch, M. Thoennessen, D. R. Chakrabarty, M. G. Herman, and P. Paul, *Phys. Rev. C* **41**, 1530 (1990).
6. M. Thoennessen, D. R. Chakrabarty, M. G. Herman, R. Butsch, and P. Paul, *Phys. Rev. Lett.* **59**, 2860 (1987).

SOFT PHOTON PRODUCTION AT LOW RAPIDITIES IN PROTON-NUCLEUS COLLISIONS AT 10 AND 18 GeV

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Experiment E855 was carried out in March at the AGS at Brookhaven National Laboratory to study anomalous soft photon production near the center of mass rapidity in proton-nucleus (Be and W) collisions at 10 and 18 GeV/c. This was the first dedicated experiment to study this phenomenon at these lower energies. This experiment was designed to measure photon production from transverse momentum (p_T) of ~ 5 MeV/c up to several GeV/c. A search will be made for soft photons in excess of hadronic bremsstrahlung, deexcitation of nuclei, and decay of neutral mesons (mostly pions). Any observed signal will be correlated with the total charged multiplicity in the event in order to determine its production mechanism. Photons produced in the decay of excited nuclei will be studied separately. The spectrum of photons from nuclei excited by incident high energy

protons gives a measure of the temperature of the excited nucleus and the amount of excitation energy which can be transferred to a nucleus in a high energy proton collision.

Two barium fluoride arrays, each consisting of 19 hexagonal elements, were used to detect the photons. One was kept in a rapidity range of +0.5 to -1.0 (designated Baf-1) and the other covered a range of -1.0 to -2.4 (Baf-2). The primary purpose of Baf-2 was to measure photons produced from deexcitations of nuclei, which were assumed to be isotropic. Both barium fluoride arrays had a veto paddle in front to reject charged particles.

A large array of scintillation counters was constructed to measure the charged particle multiplicity in events containing photons of interest. It consisted of 24 wedge-shaped counters covering a rapidity range of ± 0.5 units centered about rapidity 0 and an azimuthal range of approximately 300 degrees. The counters were 1 inch thick to give excellent pulse height resolution for discrimination between one and more than one hit in each counter. In addition, the light output uniformity was adjusted to give a uniform pulse height response of better than 10% over each counter. The whole array was mounted on a movable stand which was positioned for optimum rapidity coverage for each of the two beam energies.

A four interaction length deep hadron calorimeter was placed behind Baf-1 and was used to measure the energy leaking out of the back of the barium fluoride array. It consisted of alternating plates of copper and scintillator, and it was used to detect the presence of a large hadronic shower leakage from Baf-1. These showers could result from high energy neutrons interacting in the crystals, which are hard to distinguish from photons. The copper calorimeter was used in conjunction with TOF to reject both low and high energy neutrons.

Figure 2.25 shows the p_T spectrum for 18 GeV protons on a Be target at rapidity 0. Normalization of the data and background subtraction have yet to be completed. Presented for comparison is a Monte Carlo calculation, which uses GEANT to simulate the detector's response and FRITIOF version 1.7 to generate events for p+Be,W collisions.⁴⁻⁵ As expected, the slopes of the p_T spectra agree between the Monte Carlo and the data in the region above 400 MeV/c.

1. ORNL and Vanderbilt University.
2. Partial support provided by Joint Institute for Heavy Ion Research, ORNL.
3. Brookhaven National Laboratory.
4. B. Anderson et al., *Nucl. Phys. B281*, 289 (1987).
5. B. Anderson et al., LUND University Preprint LU TP 87-6 (1988).

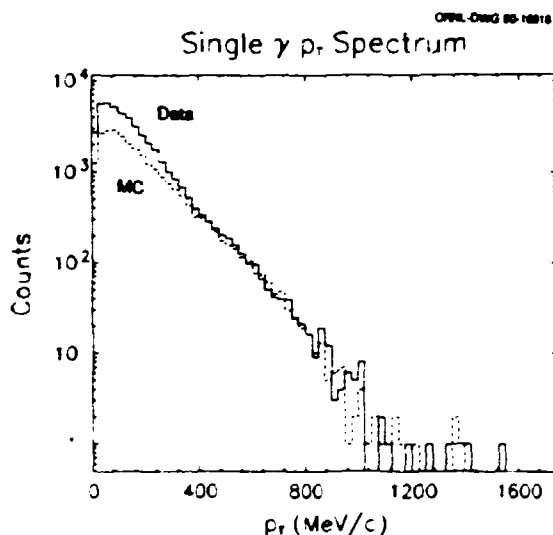


Fig. 2.25. Comparison of Monte Carlo (dashed) with experimental (bold) data.

MULTINUCLEON-TRANSFER REACTIONS FOR THE $^{50}\text{Ti} + ^{93}\text{Nb}$ SYSTEM AT SUB- AND NEAR-BARRIER ENERGIES¹

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Target and targetlike ejectiles emitted forward from ^{93}Nb -beam bombardment of thin ^{50}Ti targets were investigated at sub- and near-barrier energies using a magnetic spectrograph. Reaction products from three single-nucleon-transfer and seven multinucleon-transfer channels were observed. Multinucleon-transfer products were observed with a

sharp onset only for those collisions with apsidal distances smaller than about 12.6 fm, while single-nucleon-transfer products were observed throughout the apsidal distance range studied. Average Q -values of the multinucleon-transfer-reaction products are much more negative than the respective optimum values. These results suggest the formation of a neck at subbarrier energies.

1. Abstract of paper submitted to *Physical Review C*.
2. Legnaro National Laboratory, Legnaro, Italy.

ANGULAR MOMENTUM EFFECTS IN SUBBARRIER FUSION OF $^{64}\text{Ni} + ^{100}\text{Mo}$ ¹

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D. G. Sarantis,² and Z. Li^{2,5}

Angular momentum distribution σ_l for the compound nucleus ^{164}Yb were deduced from measurements of γ -ray multiplicity for all significant evaporation residues from fusion of ^{64}Ni and ^{100}Mo . At the lowest bombarding energies the σ_l extend to higher l values than do predictions of barrier-penetration models that include coupling of the principal inelastic channels, even if the coupling strengths are increased to match the experimental excitation function. Likewise, σ_l from a real potential with an energy-dependent shape fitted to the excitation function fails to reproduce the experimental σ_l distribution. Better success is achieved with models in which fusion occurs at large distances.

1. Abstract of published paper: *Phys. Rev. C* **40**, 2558 (1989).
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ANGULAR MOMENTUM EFFECTS IN SUBBARRIER FUSION

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The compound-nucleus angular-momentum distribution, σ_ℓ vs ℓ , for near-barrier and subbarrier fusion of ^{64}Ni and ^{100}Mo was deduced in Ref. 5 from Spin Spectrometer data on γ -ray multiplicities in coincidence with Ge photopeaks characteristic of the $2n$, $3n$, $4n$, and $\alpha 2n$ evaporation residues. The method is well suited to the high- ℓ region, say $\ell \geq 10$. Certain complications in the data acquisition and the analysis made it difficult to reach firm conclusions about the shape of the low- ℓ region of the σ_ℓ distribution. It seemed that a deeper investigation of this region would be desirable to support our conclusion in Ref. 5 that below the barrier the mean ℓ is larger than the prediction of existing barrier-penetration theories.

The first step in constructing σ_ℓ vs ℓ is to obtain distributions of the number of γ rays, k , detected for each event. Time-of-flight neutron rejection was accomplished with reference to the zero time of a given event, determined by the average of the NaI times as described in Ref. 5. Events with $k < 3$ did not provide a sufficiently good estimate of the zero time and were discarded in Ref. 5, leading to a possible loss of data for evaporation channels populating low- ℓ entry states. To compensate for this supposed loss, a constant- T_ℓ extrapolation was made in Ref. 5 from the peak region of each σ_ℓ distribution down to $\ell = 0$. This extrapolation increased the fusion cross sections and decreased the mean ℓ . We have now generated new k distributions at $E_{c.m.} = 130.1$ and 141.7 MeV by a scan of the primary data tapes without neutron rejection. The gate on NaI times was wide enough to insure that no pulses due to prompt γ rays were excluded. The peak in each new k distribution has the same shape and intensity as before, but is shifted to higher k since now all neutrons are accepted; the magnitude of the shift is as expected for the known number of neutrons and the NaI efficiency. At low k , the new distributions do not show any significant number of additional counts that might be due to γ rays missed earlier. Thus the supposed losses are negligible and the decreases in the

mean ℓ due to the extrapolation are overcorrections; the published mean ℓ should be increased by 0.5 and 1.5 at 130.1 and 141.7 MeV, respectively.

For about 90% of the primary data tapes, events with $k = 0$ were not recorded in order to avoid filling the tapes with Coulomb-excitation events. By scanning those tapes which did include the $k = 0$ events, we have shown that the $k > 0$ requirement imposed no significant loss of γ rays from evaporation residues. Two other effects will, however, modify the published⁵ cross sections slightly. (1) False vetoes of valid events may occur if the Compton suppressor surrounding each Ge counter registers a different γ ray or a neutron from that event. The fraction of such false vetoes was estimated to be about 4 to 7%, depending on the γ -ray and neutron multiplicity for a particular exit channel. (2) The fusion cross sections of Ref. 5, deduced from the extrapolations, are too large. The net effect of (1) and (2) together amounts to a 10 to 30% decrease in the published cross sections,⁵ which is insignificant compared with the discrepancies noted in Ref. 5 between experiment and various theories.

A further check on the low- ℓ magnitude of σ_ℓ is a comparison with the limit imposed by unitarity, i.e., $T_\ell \leq 1$. The $^{64}\text{Ni} + ^{100}\text{Mo}$ data do not provide a useful check because even at the highest beam energy studied, barrier penetration for all ℓ is substantially below the $T_\ell = 1$ limit. However, measurements⁵ of $^{16}\text{O} + ^{148}\text{Sm}$ (same compound system), made immediately after the ^{64}Ni bombardments and analyzed in the same way, do provide such a check. The 81-MeV ^{16}O bombardments were about 20% above the Coulomb barrier and σ_ℓ should reach the unitarity limit for low ℓ . This is in fact observed experimentally, which verifies our absolute normalization and implies that the low- ℓ data for ^{64}Ni on ^{100}Mo likewise did not suffer any significant losses.

Refinements are being made in the transformation of γ -ray multiplicity to spin. All the details of a statistical-model calculation are used to unfold an experimental γ -ray multiplicity distribution into a self-consistent estimate of the initial ℓ distribution. Preliminary results of applying this procedure produced ℓ distributions somewhat broader than in Ref. 5, but with the mean ℓ essentially unchanged.

In summary, it appears so far that there will be no significant changes in the conclusions of Ref. 5.

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2. Deceased March 1987.
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4. Present address: Physics Division, Institute of Atomic Energy, Beijing, People's Republic of China.
5. M. L. Halbert et al., *Phys. Rev. C* **40**, 2558 (1989)(see preceding abstract).

NEUTRON EMISSION IN LIGHT HEAVY ION REACTIONS¹

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Neutron emission cross sections were measured for several light heavy-ion systems, using a 4 π detector. The systems studied were $^{12}\text{C}+^{12}\text{C}$, $^{12}\text{C}+^{13}\text{C}$, $^{13}\text{C}+^{13}\text{C}$, $^{14}\text{N}+^{12}\text{C}$, $^{16}\text{O}+^{12}\text{C}$, and $^{16}\text{O}+^{16}\text{O}$ at bombarding energies around the Coulomb barrier. A detailed Hauser-Feshbach analysis was done and good agreement with the data was found. The $^{12}\text{C}+^{12}\text{C}$ system shows many resonances which are correlated to other channels. Fewer resonances are seen for the $^{12}\text{C}+^{13}\text{C}$ and $^{12}\text{C}+^{16}\text{O}$ systems.

1. Abstract of published paper: *Revista Mexicana de Fisica* **36**, No. 2, 220 (1990).
2. Instituto de Fisica, Universidad Nacional Autonoma de Mexico, Mexico, D.F.

MEASUREMENTS OF TIME DELAYS FOR PROJECTILELIKE FRAGMENTS IN THE REACTION $^{40}\text{Ar}+\text{Ge}$ AT 44 MeV/NUCLEON¹

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Crystal-blocking angular distributions have been measured for projectile-like fragments produced in bombarding a 10- μm Ge crystal with a 1.76-GeV ^{40}Ar beam. Long time delays on the order of (6-12) $\times 10^{-18}$ s were extracted and gave a direct indication of important evaporation effects. The measured times can be reproduced using a broad distribution of primary fragments of the type predicted by the abrasion model, but with excitation energies from 15 to 50 MeV, which are higher than predicted by the model. The measured time can also be reproduced assuming a narrow primary mass distribution with highly excited fragments having excitation energies of about 150 MeV.

1. Abstract of published paper: *Phys. Rev. C* **41**, 139 (1990).
2. Service de Physique Nucleaire-Basse Energie, Centre d'Etudes Nucleaires, Saclay, France.
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NUCLEAR-STRUCTURE EFFECTS IN PROTON EVAPORATION SPECTRA¹

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Energy spectra and angular distributions of evaporated protons from the reaction $^{52}\text{Cr}(^{34}\text{S}, 2\text{p}2\text{n})^{82}\text{Sr}$ at 130 MeV were measured in coincidence with discrete γ transitions. Large shifts

and changes in the shape of the proton spectra were observed when high-spin states in different rotational bands are populated. They are interpreted as due to near-yrast stretched proton emission, which preferentially populates the yrast band by subbarrier protons.

1. Abstract of published paper: *Phys. Rev. Lett.* **64**, 2129 (1990).

2. Washington University, St. Louis.

3. University of Michigan, Ann Arbor.

TARGET EXCITATION AND ANGULAR MOMENTUM TRANSFER IN REACTIONS OF $E/A = 11.9$ MeV ^{28}Si WITH ^{181}Ta FROM 4π CHARGED PARTICLE, NEUTRON, AND γ -RAY MULTIPLICITY MEASUREMENTS¹

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L. G. Sobotka,² D. W. Stracener,² J. R. Beene,
D. C. Hensley, and H. C. Griffin³

The conversion of kinetic energy into targetlike fragment excitation and orbital angular momentum into fragment spin has been studied in the reaction 333 MeV ^{28}Si with ^{181}Ta . The light charged particles were detected in a small, highly segmented, 4π phoswich detector system placed in the Spin Spectrometer, a 4π NaI array which served as a neutron and gamma detector. Multiplicities of light charged particles and neutrons detected in coincidence with projectilelike fragments indicate that the excitation energy of the targetlike fragment increases as the kinetic energy of the projectilelike fragment decreases through the quasielastic region and tends toward saturation as the kinetic energy of the projectilelike fragment approaches the kinetic energy corresponding to complete damping. Measurement of the γ -ray multiplicity in coincidence with the projectilelike fragments indicates that the angular momentum transferred to the targetlike fragment increases with decreasing mass of the projectilelike fragment for the quasielastic energy region, in contrast to the energy region corresponding to completely

damped processes, where the angular momentum of the targetlike fragment decreases with increasing mass loss from the projectile. The influence of preequilibrium processes on both excitation energy and angular momentum transfer to the targetlike fragment is discussed. These data present further evidence that ℓ waves below the entrance-channel critical angular momentum for fusion must contribute to the nonfusing reaction channels.

1. Abstract of published paper: *Phys. Rev. C* **40**, 2124 (1989).

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DEFORMATION EFFECTS IN THE COMPOUND NUCLEUS DECAY USING THE SPIN-ALIGNMENT METHOD¹

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L. G. Sobotka,² Z. Li,² T. M. Semkow,²
J. R. Beene, M. L. Halbert, D. C. Hensley,
J. B. Natowitz,⁴ R. P. Schmitt,⁴ D. Fabris,⁴
G. Nebbia,⁴ and G. Mouchaty⁴

Alpha-particle energy spectra and angular distributions with respect to the estimated spin direction of residual nuclei have been measured in heavy-ion fusion reactions. The spin direction was determined for each event by measuring the γ -ray angular correlation patterns using the Spin Spectrometer. Measurements were made for the compound nuclear systems $^{110}\text{Sn}^*$ (94 MeV), $^{114}\text{Sn}^*$ (80 MeV), $^{138}\text{Nd}^*$ (82 MeV), $^{164}\text{Yb}^*$ (67 MeV), and $^{170}\text{Yb}^*$ (135 MeV) at the indicated excitation energies as a function of the alpha-particle energy and γ -ray multiplicity. The anisotropy coefficients below the evaporation Coulomb barrier show distinct differences from $^{110}\text{Sn}^*$ to $^{170}\text{Yb}^*$. These results and the shapes of the alpha-particle spectra are compared with statistical model calculations that incorporate deformation effects in the optical model transmission coefficients. The Sn^* data can be explained without invoking deformation effects other than the ones included in the experimental yrast

lines. However, for the heavier Yb^* systems, a considerable spin-dependent deformation in the α -emission barriers is required. For these systems the α emission below the barrier is a sensitive probe for deformation that samples a broad range of excitation energies in the decay sequence.

1. Abstract of published paper: *Phys. Rev. C* 41, 2118 (1990).
2. Washington University, St. Louis.
3. Deceased March 1987.
4. Texas A&M University, College Station.

INSTRUMENTATION

GAMMASPHERE RESEARCH AND DEVELOPMENT

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J. W. Johnson, J. W. McConnell, W. T. Milner,
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Throughout the past year Physics Division staff have continued to provide support for GAMMASPHERE research and development. Significant progress has been made in several areas including those discussed below.

The performance of three proposed designs of the Compton shield has been studied using extensive Monte Carlo simulation calculations. Illustrated in Fig. 2.26 are: (1) individual, (2) honeycomb, and (3) electronics honeycomb schemes. The "individual" design which is used in all existing arrays has the advantage of simplicity, but as shown in Table 2.1, has a low peak-to-total (P/T) value because the thickness of the shield is limited by the requirement of total solid angle (4π) = 0.5 for the Ge detectors. In the "honeycomb" design, each Ge detector is surrounded by six suppressor elements and each suppressor element is shared by two Ge detectors. Since the effective thickness of the BGO is doubled, a better P/T value is achieved. However, the sharing of the shield causes false vetos of neighboring detectors and thereby reduces the efficiency of the array. In the "electronics honeycomb" design the shield elements are divided into two parts and packaged as 110 suppressors, each comprising six optically-isolated sectors. The two adjacent elements are combined electronically to suppress both Ge detectors (hence the name electronics honeycomb), except when the

neighboring Ge is triggered, then only the sector closer to the Ge is used. This design minimized the false veto and maintains the excellent P/T value of the honeycomb design. The dimensions of the electronics

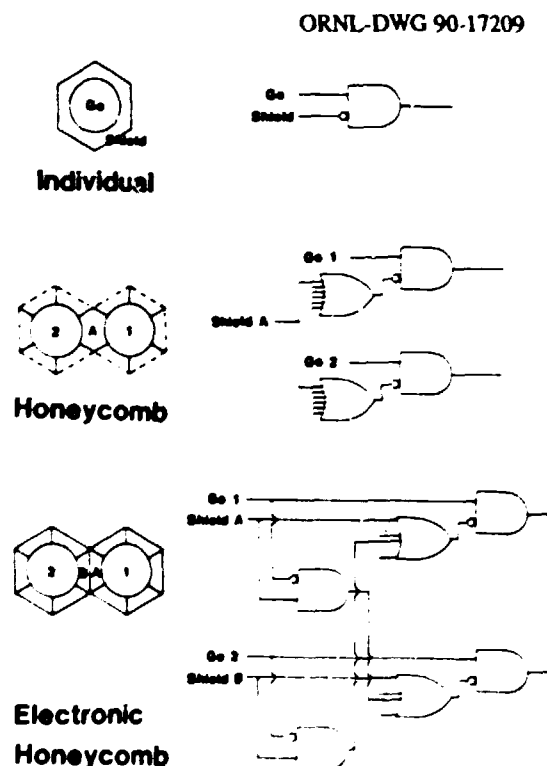


Fig. 2.26. Schematics of three types of suppressor design and suppression logic.

Table 2.2. BaF₂ cost-effectiveness analysis based on detector systems which could be purchased with \$450,000. Performance figures are for $E_0 = 15$ MeV photons. Efficiencies are relative to geometrical, and are "full energy peak" values derived by integrating spectra above $E = 13.5$ MeV (90% of E_0).

Option (see text)	No. of Units	Coverage (%)	FWHM/ E_0 (BaF only)	FWHM/ E_0 (addback)	Efficiency (BaF only)	Efficiency (addback)	$\epsilon x \Omega$
1	58	24	0.089	0.034	0.62	0.78	0.19
2	33	27	0.077	(0.029)*	0.68	(0.33)*	0.18* (0.09)*
3	9(x7)	5.4	0.053	0.053**	0.62		0.033
4	65	27	0.082	0.033	0.44	0.62	0.17

* The large shield replacement inserts of option 2 cannot be used in addback mode in the existing design, but could be used in a Compton-suppressed mode. The numbers in parentheses in addback columns for Option 2 refer to this suppressed mode. The first $\epsilon x \Omega$ given for option 2 refers to BaF₂ only operation, which yields a rather poor resolution. The second $\epsilon x \Omega$ value (in parentheses), is for suppressed mode.

** The addback mode numbers are not meaningful for the 7-pack geometry.

honeycomb design are finalized and a prototype will be ordered by Argonne National Laboratory. An important advantage of the individual packing of the BGO suppressor is the ease of removal (or replacement) of individual modules in operation and in future upgrades.

The design change of the shield from honeycomb to electronic honeycomb resulted in a reduction of the number of individually supported detectors from 470 to 110. Consequently, a new support structure consisting of 110 aluminum castings was determined to be more cost-effective than the original design of a spherical shell with 470 mounting holes. These hexagonal structure elements will be held together with self-aligning bolts to form two hemispheres. The Ge detector and BGO shield will be supported by adaptors which connect the detector to the structure elements. A sketch of the mechanical support is shown in Fig. 2.27. The support structure has a radius of 0.73 m and the beam line is 2.4 m above the floor.

Additional options for the BaF₂ inserts have become possible after the change from the honeycomb to electronic honeycomb design for the shield. Three options have been studied for their cost/performance ratios. The three options are: (1) the standard design

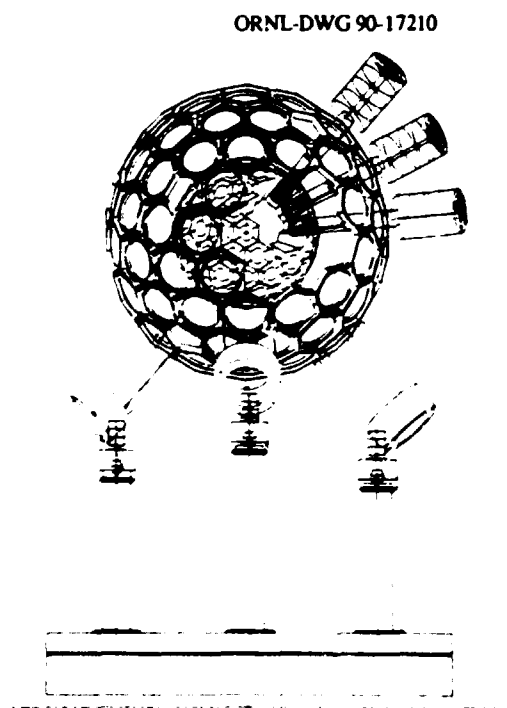


Fig. 2.27. Mechanical support structure for the GAMMASPHERE detector systems.

of replacing the Ge detectors with inserts having an overall length of 20 cm, (2) replace the shield and the Ge detector with a large crystal having a length of 20 cm and diameter of 10 cm, (3) replace the entire shield and Ge detector with a 7-pack of hexagonal detectors (6.5 cm face-to-face, 20-cm long), and (4) replace the Ge detectors with the existing ORNL hexagonal detectors. A summary of the calculated performance is given in Table 2.3. As is clear from the table, option (1) remains the most cost-effective.

Table 2.3. Performance of three types of shield from simulation calculations

Shield Design	Total Efficiency	Peak-to-Total
Individual	0.095	0.62
Honeycomb	0.079	0.70
Electronics Honeycomb	0.089	0.69

As shown in Fig. 2.28, a geometrical design of the 240-element BaF₂ innerball was developed. Because the wavelength of the BaF₂ light is in the UV region, and because the space in the GAMMASPHERE is limited, a suitable light collection method has to be found. Using a prototype BaF₂ element, we have tested several light detection options which include a quartz light guide with a

phototube, and direct coupling to photodiodes and to phototubes of various sizes. Only the direct coupling of a 1.3-cm-diam quartz window tube gives satisfactory energy and time resolution. Additional simulation calculations involving multiplicity resolution and enhancements, pile-up effects, degradation of the P/T of the Ge due to scattering effects of the innerball, etc., are being made for different BaF₂ geometries and light collection solutions as part of this research and development item. Simulations show that the reduction in P/T from scattering off the BaF₂ partially offsets the gain from reduction of false vetos. More detailed simulations and measurements with prototype units will be required to reliably estimate the gain provided by an innerball.

A VME-based parallel processor system for data acquisition has been developed (for details see "Computer Systems," Chap. 1, this report). This system has been used as a prototype for evaluating real time systems, compilers, and programing techniques for the parallel processing system of GAMMASPHERE. In addition, a processor module with four Motorola 88000 RISC processors has been tested. A total throughput of about 1.7 Mbyte/sec was achieved. Six such modules will satisfy the projected 10 Mbyte/sec data rate of the GAMMASPHERE.

Detailed design of the liquid nitrogen filling system and Ge detector annealing facility are finished. The design of the associated control systems are based on workstations and CAMAC electronics modules. The workstations will be connected to the data acquisition system through a local area network for easy access and monitoring.

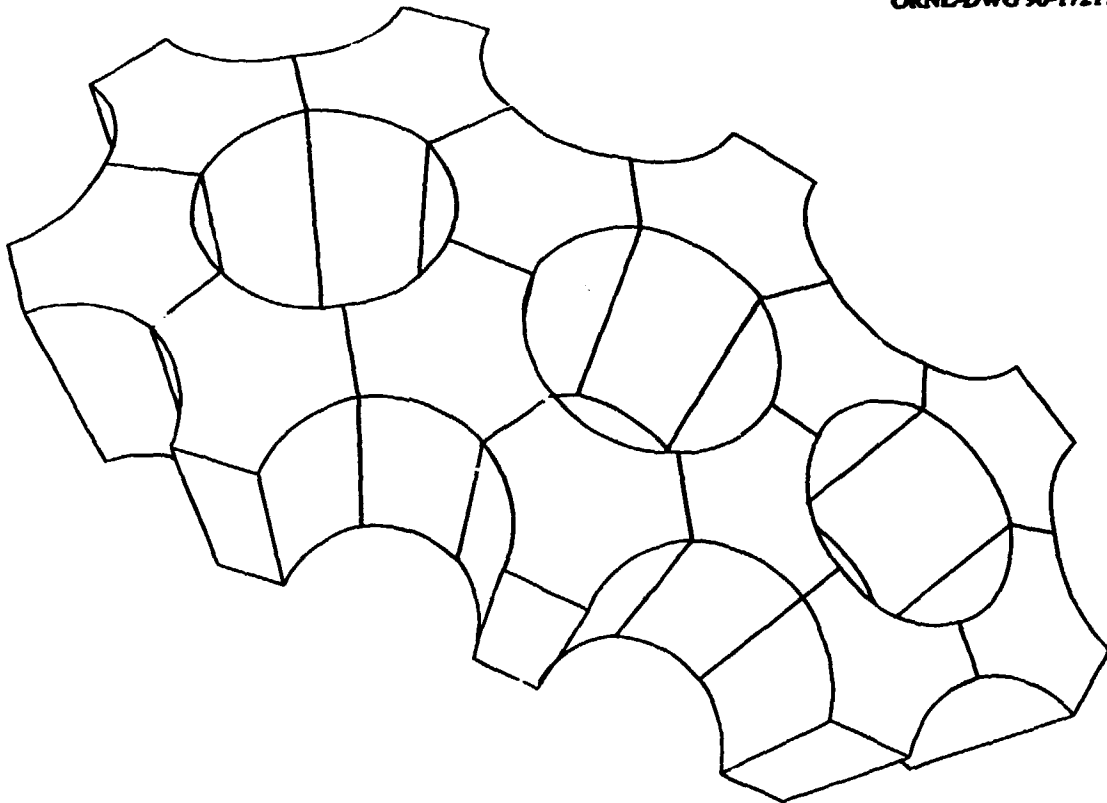


Fig. 2.28. Geometrical design of the innerball. Portion of the innerball covering the BGO shields of three Ge detectors is shown.

THE ORNL BaF_2 ARRAY

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The initial phase of the ORNL BaF_2 Array is now complete and in use for nuclear physics experiments. The array consists of 77 identical hexagonal BaF_2 crystals 6.5 cm x 20 cm long, each fitted with a Hamamatsu R2059 quartz-windowed phototube with integral tube base and magnetic shielding. The simple crystal shape was chosen so that a variety of stacking geometries could be used, however the most commonly used configuration is

expected to be in close packed blocks of 19 crystals. Mounting hardware for this configuration is available.

The full complement of 77 crystals has been available since the fall of 1989. Since that time several experiments using the array have been carried out: four at HHIRF, one at MSU, and a series of runs, including an ORNL-led experiment, at GANIL using the ORNL array combined with detectors owned by European groups (the TAPS collaboration and G.S.I.). In addition, a short but successful test run was carried out at I.U.C.F.

Most of the development work in the past year has been centered on the electronics, setup and control software, and software for data analysis.

Electronics

The requirement that the array and its associated readout electronics be easily transportable to many North American and European accelerator facilities constrained us to implement the read-out and control electronics exclusively in CAMAC. The design of the electronics also had to make allowance for and take advantage of the structure of the scintillation signal from BaF₂. About 90% of the signal is in a slow pulse, having a fall time of about 600 ns. The remaining signal forms a very fast pulse, which, when viewed through the R2059 phototube, has a rise time of ~2 ns and a FWHM of about 4 ns. The relative amount of fast and slow components varies depending on the nature of the primary radiation, but also varies from crystal to crystal. In spite of the small integrated fraction in the fast component, its pulse height is at least 5 times larger than that of the slow component for γ -ray excitation.

The analog circuitry includes a custom designed, three-way, passive splitter +500 ns delay, feeding three fast encoding, charge integrating, ADC's per crystal. Two of these, used for E_γ determination, have equal integrating times of about 1500 ns, but have gains differing by a factor of 10. The third ADC is gated for 50 ns and, together with long gate E_γ , is used for pulse shape identification and pile-up rejection.

The array is generally set up with the phototube high voltages adjusted to match the gains of all crystals as seen by the long-gate ADC's. Codes have been developed to carry out this matching automatically. Since discriminator thresholds are sensitive to the fast signal component, the variation in fast-to-slow signal ratio from crystal to crystal can result in unacceptable variation in effective thresholds. This is corrected for by individually adjustable attenuators on each detector signal before the discriminators. The analog signals to the ADC's do not pass through this attenuation.

Timing information, ADC gates, and coincidence register bits for readout control, are obtained from leading edge discriminators with thresholds set to correspond to γ energies < 100 keV. Times for individual BaF₂ crystal signals are digitized in high resolution, fast encoding TDC's. Custom designed logic delay modules in the timing circuitry provide up to 600 ns of adjustable delay with less than 100 ps of

jitter, allowing us to take advantage of the excellent timing of BaF₂ for time-of-flight measurement.

Experiments utilizing the BaF₂ array generally focus on high energy (10 to 100 MeV) γ radiation. Consequently, the standard electronics makes provision for triggers based on large pulse height signals. Individual high threshold discriminators are provided for each detector and analog sum energies are constructed for physical detector blocks. Logic signals depending on the multiplicity of high-threshold events in the individual discriminators, or signals from discriminators on the analog sums can be used for trigger construction.

Additional features of the electronics include custom designed CAMAC modules which allow the linear and logic signals from any crystal in the array to be multiplexed onto a single pair of coaxial cables, under computer control.

Response Construction and Unfolding

Quantitative analysis of the complex continuum spectra of high-energy γ -rays produced in a typical experiment requires a detailed knowledge of the response of the array to radiation. Software has been developed for constructing a parametric form of the detector response from a small set of experimental measurements or Monte Carlo simulations. For example, we have found that the parameters of the response can be adequately determined for the range 1 MeV to 100 MeV with input spectra at fewer than ten strategically chosen energies. Once this is done, the software can generate a complete absolute response matrix on any chosen energy grid within the range covered by the input. The selection of numerical representations which are sufficiently accurate, and which result in parameters that vary smoothly enough with energy for efficient and accurate interpolation, was a major part of the development of this package. We have developed parameterized 1 to 100 MeV responses for several of the standard experimental geometries as part of testing and verification of the response generation package.

Because of the need for responses in particular experimental geometries and the difficulty of producing monoenergetic sources of γ -radiation in the required energy range, we have relied heavily on Monte Carlo simulations, using the codes based on

the GEANT³ package. We have tested these simulations extensively against experimental data, and find good agreement over a wide energy range. We continue to refine and improve our simulation technology.

One common use of the response matrices generated in this way is to "unfold" experimental pulse height spectra into absolute distributions of primary gamma-ray yield. During the course of development of software for the automated construction of responses, we have developed new and particularly robust unfolding routines based on the methods of iterative improvement developed for solutions of linear systems in the presence of noise.⁴⁻⁶

Analysis Software

The first set of complex experiments utilizing the BaF₂ array at HHIRF presented us with a crisis in the time required for processing event-by-event data tapes. This led us to initiate an effort to acquire fast RISC/UNIX based processors, and adapt the standard HHIRF analysis package to run on this platform. This successful effort is discussed elsewhere in this report.

1. Instrumentation and Controls Division, ORNL.

2. Great Lakes Colleges undergraduate student, Carleton College, Northfield, Minnesota.

3. R. Brun et al., GEANT code, CERN Report DD/EE/84-1 (1987).

4. S. P. Sorensen, *Nucl. Phys. A* **461**, 487c (1987).

5. W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes, The Art of Scientific Computing* (Cambridge University Press, Cambridge, 1986).

6. N. Gastinel, *Linear Numerical Analysis* (Academic Press, New York, 1970).

THE HILI - A MULTIDETECTOR SYSTEM FOR LIGHT IONS AND HEAVY IONS¹

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A detector system with a large acceptance, high granularity, and a logarithmic response, has been built. It is well suited to detect, simultaneously, heavy and light fragments from nucleus-nucleus collisions at energies higher than 10 MeV/nucleon. The angular range spanned by this detector system is $\pm 20^\circ$ in-plane and $\pm 16^\circ$ out-of-plane with the exclusion of a 2.5° cone around the beam axis. Coverage with a large dynamic range is provided with 4 large, gas-filled ionization chambers and behind them a 192-element hodoscope made of individual fast+slow plastic scintillation telescopes in a 'phoswich' arrangement.

1. Abstract of paper submitted to *Nuclear Instruments and Methods*.

2. Joint Institute for Heavy Ion Research, ORNL.

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3. HIGH-ENERGY REACTIONS

FORWARD ENERGY PRODUCTION IN ^{32}S -INDUCED HIGH-ENERGY NUCLEAR COLLISIONS

WA80 Collaboration

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The forward energy, E_F , in WA80 is defined as the sum of the energy of all particles with scattering angles smaller than $\approx 0.3^\circ$. The E_F spectra for heavy-ion-induced reactions, as shown in Fig. 3.1, can be qualitatively understood based on the following simple arguments: For peripheral collisions, E_F will be dominated by the energy carried by projectile spectators, resulting in large values of E_F . Since the differential cross section is increasing with impact parameter, the E_F spectra will be increasing for large E_F until trigger cuts set in at $\approx 88\%$ of the beam energy. For central collisions, where most or all of the projectile nucleons are participating, only the energy carried by the most forward-going leading particles and reaction products will reach the ZDC, resulting in small values of E_F . The range of impact parameters, b , where the whole projectile will react with the target, is approximately given by $b < R_t - R_p$, where R_p and R_t are the radii of the projectile and target, respectively. The cross section for central

events in asymmetric collisions ($A_p < A_t$) can therefore be expressed as

$$\sigma_{\text{central}} = \pi (R_t - R_p)^2 = \pi r_0^2 (A_t^{1/3} - A_p^{1/3})^2. \quad (1)$$

$$r_0 = 1.2 \text{ fm}.$$

The "bump" observed at $\approx 0.1 \cdot E_{\text{beam}}$ in the E_F spectra for the heaviest targets corresponds to these central events, and as seen from Eq. (1), the size of it will increase with increasing target mass.

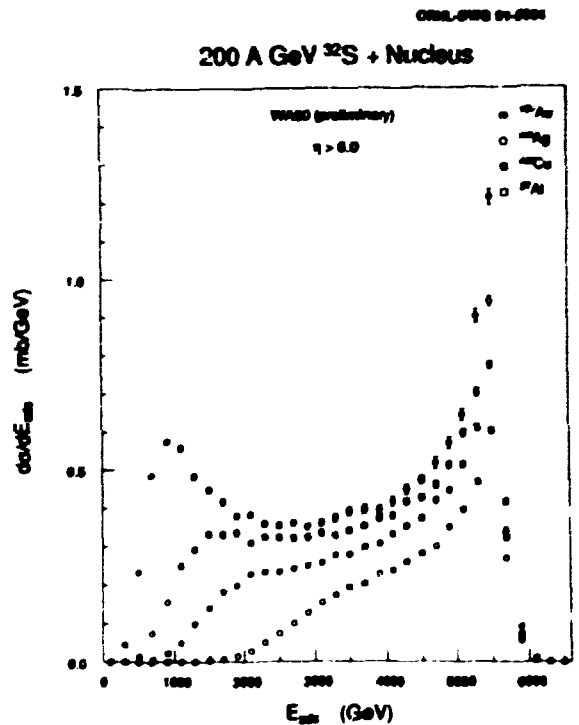


Fig. 3.1. Forward energy spectra for 200-A-GeV ^{32}S -induced reactions. The error bars reflect the statistical errors. At energies below 5500 GeV, the spectra are corrected for distortions caused by trigger cuts and background events.

The importance of the nuclear geometry in the determination of the shape of energy spectra in high-energy nuclear collisions can be nicely illustrated by the following scaling law. The shape of the E_F spectra at 200 A GeV scales approximately with the ratio R_t/R_p or, stated more precisely,

$$\frac{d\sigma}{d\varepsilon} = \sigma_{\text{tot}} f\left(\varepsilon, \frac{R_t}{R_p}\right);$$

$$\varepsilon = E_F/E_{\text{beam}}; \quad (2)$$

$$\sigma_{\text{tot}} = \pi r_0^2 (A_t^{1/3} + A_p^{1/3})^2.$$

Examples of this scaling law are the similarities between the E_F spectra for O + Ag and S + Au, where the ratios between the radii are 1.89 and 1.83, respectively, and the spectra for O + C and S + Al with ratios of 0.91 and 0.95, respectively.

In any analysis of data obtained with other WA80 detectors for different projectile-target combinations, it is important to be able to perform comparisons for similar event classes such as, e.g., central events ($b < R_t - R_p$) or peripheral events ($b > R_t$). This requires a method for estimating the impact parameter on an event-by-event basis. For this purpose, the following procedure has been developed. The basic assumption is that E_F depends monotonically on b . From this follows that the impact parameter b_0 , corresponding to a particular value E_F^0 of the forward energy, can be estimated from

$$\pi b_0^2 = \int_0^{E_F^0} \frac{d\sigma}{dE_F} dE_F, \quad (3)$$

where $d\sigma/dE_F$ is the E_F spectrum. Computer simulations based on FRITIOF and VENUS indicate that this method allows b to be estimated to within ± 1 fm, except for the most central events for asymmetric systems, where the monotonic correlation between b and E_F is washed out for $b < R_t - R_p - 1$ fm.

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TRANSVERSE ENERGY PRODUCTION IN PROTON- AND ^{32}S -INDUCED HIGH-ENERGY COLLISIONS

WA80 Collaboration

(For a complete list of authors, see first writeup in this section.)

Based on the new algorithm for extracting $dE_T/d\eta$ from the WA80 calorimeter data,¹ all the available data have been reanalyzed. All E_T spectra have been obtained by integrating the $dE_T/d\eta$ distributions from 2.4 to 5.5 in η on an event-by-event basis. The values of E_T extracted by using the new method deviates typically less than 5% from the values in Ref. 2, which is considerably lower than the overall uncertainty in the energy scale of 10%. All spectra have been corrected for background events, which influence the spectra only at very low values of E_T .

The proton-induced E_T spectra in Fig. 3.2 are quite featureless. The falloff at low E_T values is caused by trigger bias. The produced E_T of 15 GeV at the 10^{-3} mb level for 200-GeV p + Au is considerably lower

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200 A GeV P + Nucleus

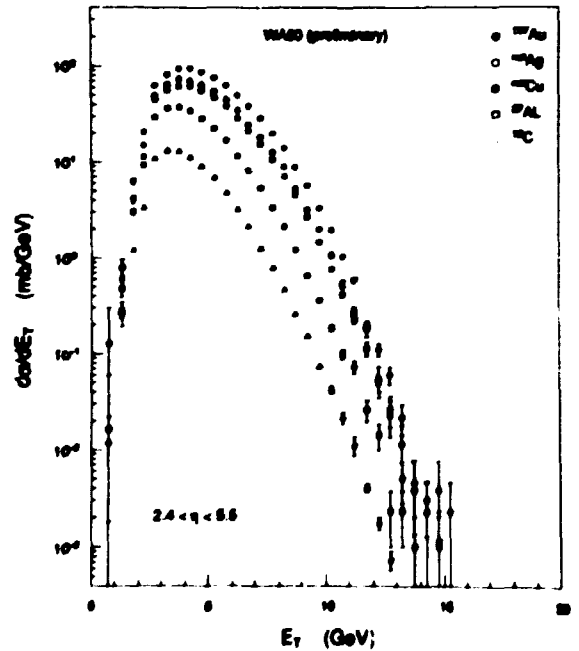


Fig. 3.2. Transverse energy spectra for 200-GeV proton-induced reactions. The absolute cross section scale is tentative and awaits target-in / target-out corrections.

than the value of 40 GeV reported by the HELIOS collaboration³ for 200-GeV p + Pb. It should, however, be emphasized that WA80 are measuring in the forward interval of $2.4 < \eta < 5.5$; whereas, HELIOS is measuring in the backward interval of $0.6 < \eta < 2.4$. On the other hand, NA35 (Ref. 4), with an acceptance of $2.3 < \eta < 3.9$, has reported a value of 15 GeV, which is identical to our value.

The ^{32}S -induced E_T spectra are qualitatively very similar to the ^{16}O induced.² A comparison shows that in the tail region at large E_T values the ratio between E_T for S + Au and O + Au is 1.65. This value is, however, strongly dependent on the particular η interval over which E_T is integrated.

1. WA80 Collaboration, *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1989*, ORNL-6578, pp. 91-93.

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3. NA34 Collaboration, T. Åkesson et al., *Z. Phys. C* 38, 397 (1988).

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$dE_T/d\eta$ DISTRIBUTIONS IN ^{16}O - AND ^{32}S -INDUCED HIGH-ENERGY NUCLEAR COLLISIONS

WA80 Collaboration
(For a complete list of authors,
see first writeup in this section.)

All the available data from the WA80 calorimeters have been analyzed with our new algorithm¹ for extracting $dE_T/d\eta$. As a typical example, Fig. 3.3 shows the centrality dependence of the $dE_T/d\eta$ spectra for 200-A-GeV S + Au. The three distributions correspond to (a) central collisions ($b < R_t - R_p$), (b) intermediate collisions ($R_t - R_p < b < R_t$), and (c) peripheral collisions ($b > R_t$). The approximate information on the impact parameter has been obtained from the forward energy spectrum.² The solid lines in the figure are gaussian fits to the data and have been used to extract the information on centroids, widths, and maximum values as discussed below. As a function of decreasing impact parameter, (a) the maximum value of $dE_T/d\eta$ increases from 13 GeV for peripheral collisions to 94 GeV in central collisions, (b) the centroid decreases from $\eta = 3.0$ to $\eta = 2.5$, and (c) the width decreases from $\sigma = 1.7$ to σ

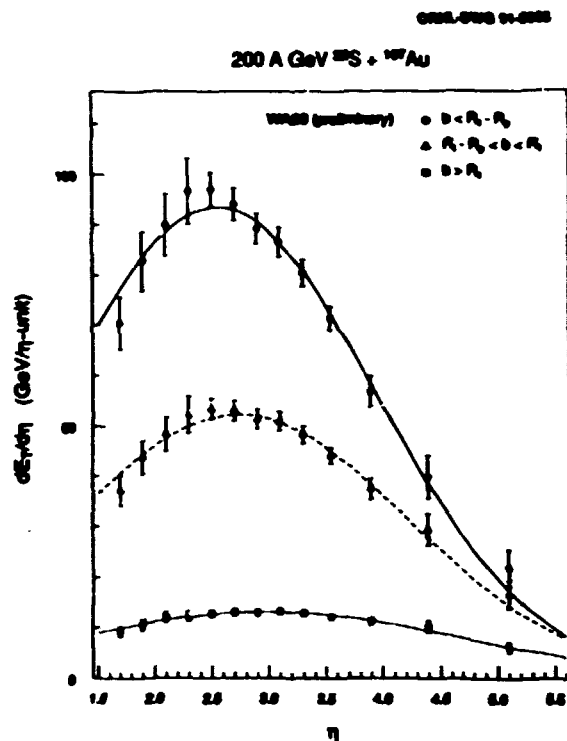


Fig. 3.3. Centrality dependence of $dE_T/d\eta$ for 200-A-GeV $^{32}\text{S} + ^{197}\text{Au}$. See text for further information.

≈ 1.4 . All these variations can be well understood with simple models based on counting the number of projectile- and target-participant, W_p and W_t , respectively. As shown earlier,³ the E_T production scales approximately with the number of participants causing $(dE_T/d\eta)_{\text{max}}$ to increase with decreasing impact parameter. Similarly, for a light projectile hitting a heavy target, the ratio W_p/W_t will decrease with increasing centrality. This will cause the effective c.m. system to move backwards as expressed in the following approximate formula for the effective c.m. rapidity, $y_{\text{c.m.}}$:

$$y_{\text{c.m.}} \approx \frac{1}{2} \left(y_p + y_t + \log \frac{W_p}{W_t} \right).$$

The width dependence demonstrates how the participants are becoming increasingly more stopped as they have to transverse more nuclear matter in the central collisions, causing a larger fraction of the transverse energy to be emitted at midrapidity. A point of some controversy has been the projectile mass dependence of E_T in central collisions. As can be seen from Fig. 3.4 this dependence is strongly rapidity dependent. In the projectile rapidity region (high η), $dE_T/d\eta$ increases approximately linearly

with A_p ; whereas, in the target rapidity region the dependence is much weaker. The scaling factor of 1.67 mentioned in Ref. 4 corresponds well to the average ratio between the two spectra in Fig. 3.4 in the interval $2.4 < \eta < 5.5$. Please refer to Ref. 5 for further details on the scaling properties of $dE_T/d\eta$.

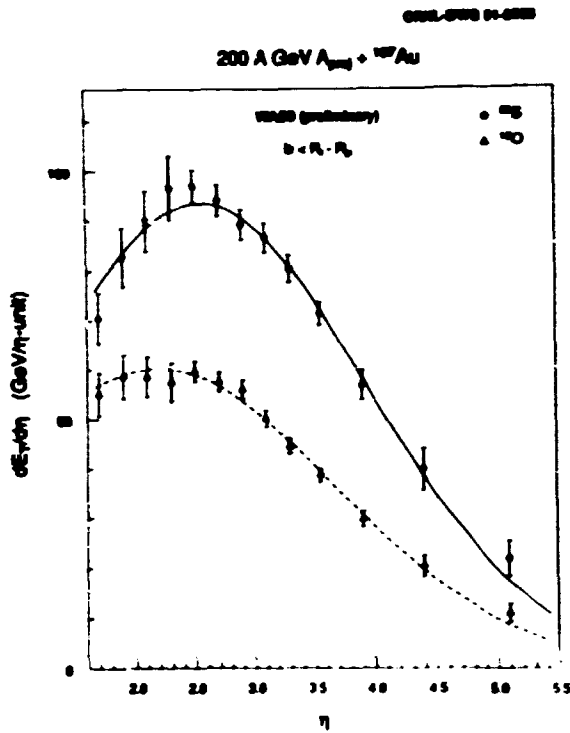


Fig. 3.4. Projectile dependence of $dE_T/d\eta$ in central collisions for 200-A-GeV $A_p + 197$ Au.

1. WA80 Collaboration, *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1989*, ORNL-6578, pp. 91-93.

2. "Forward Energy Production in ^{32}S -Induced High-Energy Nuclear Collisions", WA80 Collaboration, this report.

3. WA80 Collaboration, R. Albrecht et al., *Phys. Lett. B* 199, 297 (1987).

4. "Transverse Energy Production in Proton- and ^{32}S -Induced High Energy Collisions", WA80 Collaboration, this report.

5. "A Universal Parameterization of $dE_T/d\eta$ in High-Energy Nuclear Collisions," WA80 Collaboration, this report.

A UNIVERSAL PARAMETERIZATION OF $dE_T/d\eta$ IN HIGH-ENERGY NUCLEAR COLLISIONS

WA80 Collaboration

(For a complete list of authors,
see first writeup in this sect.)

Based on the large amount of data available on E_T from CERN and BNL the target and projectile dependence of this global quantity has recently received a lot of interest. Reference 1 gives a good summary of the current situation. A universal scaling has been difficult to obtain as long as the scaling variables have been chosen as the projectile and target masses, A_p and A_t . As a continuation of our previous work,² in which WA80 has stressed the importance of incorporating the number of participants in a consistent description of high-energy nuclear collisions, we present below a universal parameterization of $dE_T/d\eta$ for a given impact parameter, b . The key ingredient in this parameterization is the use of the number of projectile and target participants, W_p and W_t for the particular value of b , instead of the total masses A_p and A_t . Once these participant variables have been chosen, a symmetric description between projectile and target can easily be obtained.

The functional expression for the parameterization of $dE_T/d\eta$ is

$$\frac{dE_T}{d\eta}(b) = G(\eta) W_p \alpha(y_p, \eta) W_t \alpha(\eta - y_t);$$

$$G(\eta) = \frac{N}{\sqrt{2\pi}\sigma_\eta^2} \exp\left\{-\frac{1}{2} \frac{(\eta - \eta_0)^2}{\sigma_\eta^2}\right\};$$

$$\alpha(x) = \left(1 + \exp\left\{\frac{x - \eta_0}{\sigma_\eta}\right\}\right)^{-1}.$$

W_p and W_t can be determined either by numerical integration using Glauber theory^{3,4} or from Swiatecki's analytical expressions.⁵ For central collisions Ref. 5 gives

$$W_p = A_p;$$

$$W_t = A_t [1 - (1 - \mu^2)^{3/2}] \sqrt{1 - (\beta/v)^2};$$

$$v = R_t / (R_t + R_p);$$

$$\beta = b / (R_t + R_p);$$

$$\mu = R_p / R_t;$$

$$R = 1.20 A^{1/3} \text{ fm}.$$

The four free parameters (N , η_0 , σ_η , and σ_η) are found from least-squares fitting to the available WA80 data to be

$$N = 2.4 \log (\sqrt{s} - 2.0) \text{ GeV} ;$$

$$\eta_0 = (y_p + y_t)/2 + 0.2 ;$$

$$\sigma_a = 0.22 (y_p - y_t) ;$$

$$\sigma_a = 0.09 (y_p - y_t) ;$$

$\sqrt{s}$ is the c.m. energy in GeV of the $W_p + W_t$ system. y_p and y_t are the projectile- and target-rapidities, respectively. The tested limits of applicability of this parameterization is $16 < A_p < 32$, $12 < A_t < 197$, $10 < \sqrt{s} < 20$ GeV, $1.6 < \nu < 5.5$, and $b < R_t$. Within these limits the accuracy is always better than 25% and in most cases better than 5-10%.

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2. WA80 Collaboration, R. Albrecht et al., Phys. Lett. B 199, 297 (1987).
3. R. J. Glauber, in *Lectures in Theoretical Physics*, Vol. 1, pp. 315. W. E. Brittin, L. G. Durham (eds.), New York, Interscience 1959.
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COMPARISON BETWEEN WA80 CALORIMETER DATA AND MONTE CARLO SIMULATIONS OF HIGH-ENERGY NUCLEAR COLLISIONS

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An important way of gaining a deeper understanding of the large amount of data WA80 has collected at CERN is to make comparisons to Monte Carlo simulations of high-energy nuclear collisions done with a variety of different computer codes. These codes are generated from a multitude of models that differ in their fundamental assumptions: Are the fundamental entities partons or hadrons? Are gluon strings formed? If so, how are they formed? How do they fragment into hadrons? How is the superposition from nucleon-nucleon collisions to nucleus-nucleus collisions done?, etc.

At ORNL/UTK we have built up a library of these models¹ and have now started a systematic comparison between the models and the data. As an example, Fig. 3.5 shows the transverse energy spectra

for 200-A-GeV $^{32}\text{S} + ^{197}\text{Au}$ collisions for $2.4 < \eta < 5.5$, both for the WA80 experimental data (solid lines) and for four different models. FRITIOF 1.07 (Ref. 2) is based on the LUND string picture; VENUS 3.05 (Ref. 3) and MCFM (Ref. 4) are based on the Dual Parton Model; and MARCO⁵ is based upon a phenomenological parametrization of nucleon-nucleon collisions. The general shape of the E_T spectra is well reproduced by all the models, but there are distinct differences in the magnitude of the produced E_T . Interestingly, the two codes based on the DPM differ significantly from data. VENUS overestimates E_T with $\sim 25\%$ and MCFM underestimates with $\sim 10\%$. FRITIOF and MARCO are reproducing the data well in this particular case.

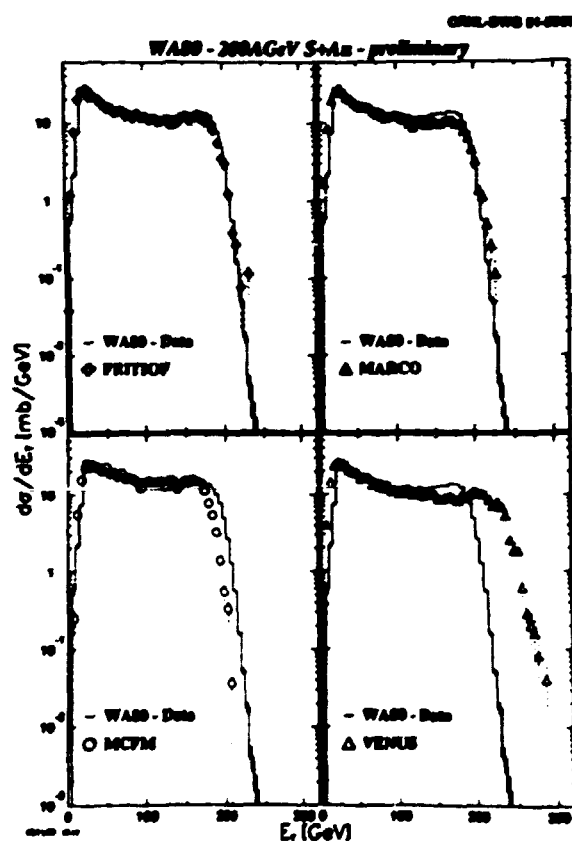


Fig. 3.5. Comparisons between E_T spectra from WA80 data and four different Monte Carlo models. The colliding system chosen is 200 A-GeV S + Au in the interval $2.4 < \nu < 5.5$.

Systematic studies, however, show that a meaningful evaluation of the models cannot be done based on a single spectrum. If comparisons are made at smaller η values, VENUS is doing much better, whereas FRITIOF and MARCO underestimate the E_T production. This effect is probably due to the

addition in VENUS of secondary interactions, both among the produced particles themselves and between the produced particles and the surrounding spectator material. The importance of secondary interactions will increase in the target fragmentation region for light projectiles bombarding heavy targets.

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NUCLEAR STOPPING POWER

S. P. Sorensen¹

Universally accepted estimates of the nuclear stopping power in heavy-ion collisions have been difficult to obtain because of a proliferation of definitions of the concept. WA80 (Ref. 2) and NA34 (Ref. 3) have advocated the use of the "integrated energy stopping" S_{int} , defined as the ratio between the experimentally measured total E_T integrated over the full η range and the isotropic fireball limit for central collisions:

$$S_{int} = \frac{E_T^{exp}}{E_T^{max}}$$

$$E_T^{exp} = \int_{-\infty}^{\infty} \frac{dE_T^{exp}}{d\eta} d\eta$$

$$E_T^{max} = \pi/4(E_{cm} - M_w c^2);$$

where M_w is the total mass of the participants. In most cases some kind of extrapolation is needed in order to evaluate $dE_T/d\eta$ in regions of η with no calorimeter coverage, which naturally introduces a large amount of uncertainty in this procedure.

Another measure of stopping, introduced by WA80 (Ref. 2), has been the "midrapidity energy stopping" S_{mid} defined as

$$S_{mid} = \frac{(dE_T^{exp}/d\eta)_{mid}}{(dE_T^{iso}/d\eta)_{mid}};$$

$$(dE_T^{iso}/d\eta)_{mid} = (E_{cm} - M_w c^2)/2.$$

This measure is easy and reliable to calculate and is closely related to the maximum attainable energy density.

A third approach by Stachel and Braun-Munzinger,⁴ based on the Landau fireball model, has estimated the total energy contained in the fireball to be around 90% of the available c.m. energy, consistent with a momentum degradation length of 5 fm. It should be noted that an energy-independent momentum degradation length, as would be expected by the constant nucleon-nucleon cross section at $\sqrt{s} > 3$ GeV, will result in a constant ratio between the fireball energy and the c.m. energy. This does not, however, necessarily indicate full stopping, which should be defined as the situation where the average final rapidities of the projectile and target participants are the same ($S_y = 1$, see below).

From leading baryon spectra, the momentum degradation length Λ in p + A reactions⁵ has been determined to be 6 ± 2 fm, corresponding to a rapidity shift of 2.4 in central p + Pb collisions. Based on the WA80 E_T and forward energy spectra, Wong⁶ determined the effective momentum degradation length in ^{16}O -induced reactions at 60 and 200 A GeV to be approximately 4 fm, indicating a very large degree of stopping in nuclear collisions.

Among the many measures of nuclear stopping, we would like to propose the use of the following measure S_y ,

$$S_y = \frac{\langle y_p - y_t \rangle + \langle y_t - y_l \rangle}{y_p - y_l},$$

where $y_{p,t}$ is the rapidity of projectile or target and $\langle y_{p,t} \rangle$ is the average rapidity of the projectile or target participants after the collisions. From the following formula for the rapidity shift in central collisions of the projectile participants,

$$\langle y_p - y_t \rangle = \frac{2r_0 A_p^{1/3}}{\Lambda} \quad r_0 = 1.2 \text{ fm},$$

and an equivalent formula for $\langle y_t - y_l \rangle$, we find the following expression for the nuclear stopping power in terms of Λ and $y_p - y_l$,

$$S_y = \frac{2r_0 A_p^{1/3} + A_l^{1/3}}{\Lambda (y_p - y_l)}.$$

Values of $S_y \leq 1$ correspond to full stopping. For the system $^{16}\text{O} + \text{Au}$ with $A = 4$ fm, S_y will be 1, 0.8, and 0.5 at AGS, SPS, and RHIC energies, respectively. A more detailed analysis taking the curvature of the nuclei into account is outside the scope of this progress report.

1. Adjunct research participant from the Univ. of Tennessee, Knoxville.
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BGO PHOTON DETECTOR

WA80 Collaboration

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One of the most promising suggested signatures of quark-gluon plasma (QGP) formation in relativistic heavy-ion collisions is the enhanced direct radiation of photons. The High-Energy Reactions Group at ORNL is presently involved in direct photon measurements in relativistic heavy-ion collisions through the WA80 experiment at CERN using Pb-glass photon detectors in reactions of 200-A-GeV beams of oxygen and sulfur.¹ It is of interest to continue the direct photon measurements under circumstances more favorable for QGP formation with heavier projectiles, when Pb beams will become available at CERN, and at higher incident energies at RHIC. Since the direct photon enhancement is expected to be most evident at low transverse momenta, p_T , it is desired to develop a photon detector which will allow the measurements to be pursued to the lowest possible p_T . In order to extract the direct photon contribution, it is necessary to measure simultaneously the photon contributions from π^0 decays also in the low p_T region. However, due to the high π^0 multiplicity of heavy-ion-induced reactions, there is a large combinatorial background of photon pairs from which the π^0 yield must be extracted. This problem increases with increasing mass or energy of the colliding system, according to

the increase in the π^0 particle density. To combat this problem, it is necessary to minimize the two-photon invariant mass resolution by using a detector system with the best possible energy and position resolution. From published information and GEANT simulations, it was realized that BGO provided the best resolution with the least cost per pixel element. Since this is also the solution which was chosen by the L3 experiment at LEP after extensive tests, we have largely followed their design. The WA80 BGO modules are right cylinders of 2.5 cm x 2.5 cm front surface and 22 radiation lengths depth. They are read out by two Hamamatsu photodiodes ($2 \times 0.75 \text{ cm}^2$), which nearly cover the back surface (the same diodes as used by L3). In order to exploit the excellent resolution of BGO over the full dynamic range of a few MeV to around 100 GeV, a custom pre-amplifier/amplifier/ADC system has been designed and built in the ORNL I&C Division. The ORNL system is similar to that of L3 in that six different amplification ranges are used together with an 11-bit ADC to provide an effective 20-bit readout system. Although somewhat similar in philosophy to the L3 design, the ORNL design is significantly different in that it follows more closely a nuclear physics spectroscopy approach using pulse-shaping, baseline restoration, and a track-and-hold stage, rather than using gated pulse integration. This is partly motivated by the difference between running in a collider geometry with a known interaction time and the possibility of a clocked trigger, and a fixed-target geometry with interactions occurring at random times over a long spill period.

An array of 30 BGO modules was assembled and used to study the response of the BGO detector and to test the electronic readout at various prototype stages, the last stage of which is still under design. The preparation work with the BGO consisted of acceptance tests, including measurements of the light transmission using the L3 transmission test bench, resolution measurements with a ^{137}Cs source, and physical dimension measurements. Also, tests were made of different surface coverings to optimize the uniformity and amount of light collection (wrapping with Millipore filter paper was found to be optimum). Measurements were made with the photodiodes using a ^{57}Co source and with cosmic rays in the BGO to obtain absolute measurements of the number of electron pairs in the photodiode per MeV of deposited energy in the BGO in order to determine the necessary absolute amplification ranges and to study the noise behavior of the diodes to find the optimum amplifier shaping time. A shaping time of 2 μs was found to give an optimum noise

contribution of about 1000 electron-hole pairs, corresponding to about 1 MeV of energy deposited in the BGO.

*New members on this project include C. L. Britton, M. N. Ericson, and A. L. Wintenberg (ORNL I&C Div.); M. Hartwig (Univ. of Münster); J. K. Pope (ORAU/ORNL Graduate Student Research Participant); and V. Manko and M. Ippolitov (Kurchatov Institute).

1. Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1989, ORNL-6578, p. 93.

BGO PHOTON DETECTOR PERFORMANCE

WA80 Collaboration

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The BGO array of 30 modules described in "BGO Photon Detector" was used in test beams on the X3 beam line at CERN in a two-week test period in late December 1989 and in a six-week period in April-May 1990. During these test periods the BGO was read out with prototypes of the ORNL preamplifier, but with commercial amplifiers and 11-bit ADCs. From these test results, it was observed that the electronic noise contribution to the resolution corresponded to about 1 to 2 MeV, which was below the channel resolution used during the tests due to the limited dynamic range of the commercial readout. The light output of the BGO was observed to decrease by about 1% per degree C of temperature increase. This temperature dependence is similar to that quoted by L3, although apparently about 30% smaller. It was observed that part of the observed temperature drift could be attributed to electronic drift as seen by drift of the electronic pulser signal. The position resolution of the BGO has been found to be extremely good, with a value of about 1 mm at 10 GeV obtained without fitting of the shower, but instead, by using a simple weighted average method, but using logarithmic rather than linear weights. The same procedure used for the higher position moments seems to provide an efficient means to discriminate between photons and hadrons with essentially no hadron contamination above 1 GeV.

The 30-element BGO array was also used in the August 1990 sulfur run of WA80. For this run

period the BGO elements were read out with prototypes of the preamplifiers and amplifiers of ORNL design and construction. These amplifiers provide 6 different gain ranges, which vary over a factor of 512, with a sample-and-hold circuit and a multiplexer which selects as output from the module the highest unsaturated gain range to be digitized with a commercial 11-bit ADC. It also provides 3 bits of information to give the selected gain range and to be read out with a commercial latch. In this way, the system provides an effective 20-bit dynamic range. In the final design stage the commercial ADCs will be replaced by a custom readout multiplexer and commercial ADC module which will interface to the data acquisition system through VME. These modules were found to perform exactly as designed. During the run period it was decided to make several modifications, mainly to lower the low-energy threshold to around 10 MeV, and also to improve the timing of a slow coincidence with the WA80 trigger to validate the BGO readout. Although this BGO array is of very modest size, it should provide interesting physics information on the inclusive photon spectra, especially at very low energies, which can be compared with the large Pb-glass arrays of WA80. It will also provide some early indications of whether it is highly sensitive to low-energy background which might degrade the energy resolution from that obtained in a clean test environment. This information can be studied both from the observed resolution for the minimum ionizing peak as compared to that seen under the test conditions, and also from the π^0 mass resolution when the BGO information is combined with that from the Pb-glass detectors.

*New members on this project include C. L. Britton, M. N. Ericson, and A. L. Wintenberg (ORNL I&C Div.); M. Hartwig (Univ. of Münster); J. K. Pope (ORAU/ORNL Graduate Student Research Participant); and V. Manko and M. Ippolitov (Kurchatov Institute).

DATA ANALYSIS FOR WA80 USING THE ACP FARM

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A major problem in high-energy nuclear physics is the processing of the large amount of data accumulated. At ORNL we have tried to overcome this problem by utilizing a parallel computer system ACP (Fermilab Advanced Computer Project). This parallel computer with no communication between the parallel nodes is especially cost-effective for processing nuclear collision data, where each node independently of its neighbors can analyze an event.

During 1990, data summary tapes (DSTs) were produced from WA80 proton data using two ACP farms. Each farm¹ had 19 nodes and was connected to a VAXstation II/GPX as the host computer. The data was read from 8-mm videotapes by the host computer, which transfers the event after a first check to the next available node. If a node signals that it finished an event, the data are picked up by the host and written to another 8-mm videotape. For these data the limiting factor in the event processing is the transfer speed of the ACP-Farm Bus. By splitting the available nodes into two farms, the overall speed could be increased. In total, close to 7 million events were processed.

Each 8-mm videotape has a capacity of 2 Gbyte and contains, on the average, 40 runs, or 700,000 events (60% tape capacity). The processing of one tape took 3 to 5 days of continuous processing, depending on the projectile-target system. Figure 3.6 shows the CPU time per event and node for all processed projectile-target systems. Every event has to fulfill cuts on the trigger counters before it is processed. This accounts for the high number of events with small CPU time, since the proton-beam data had significantly more halo and random events than we encountered with data-taking using heavy-ion beams. With an average of about 11 seconds of CPU time per event, processing the data on a VAX 780 would have taken more than 17,000 h (~2 years) of CPU time. The DST tapes were copied and shipped to the University of Münster (Germany), where the data for the lead-glass detector SAPHIR are currently being analysed.

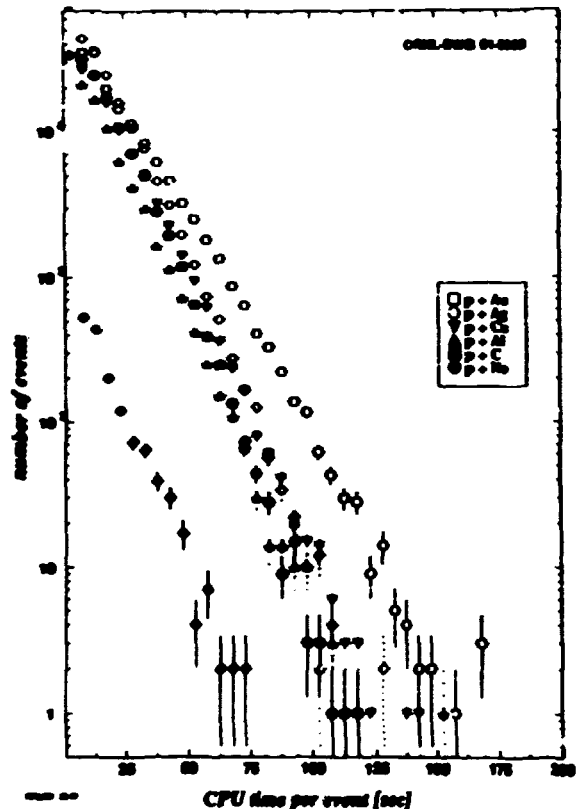


Fig. 3.6. Processing time per event and ACP node for WA80 proton data.

1. "Data Summary Tape Production Using the ACP Farm," *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1989*, ORNL-5578.

IMPLEMENTATION OF HIGH-ENERGY NUCLEAR COLLISION MODELS ON THE INTEL/i860 HYPERCUBE

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The extremely large particle multiplicities which will be encountered at RHIC are a large problem not only for the detector hardware, but also for the computer simulations necessary for designing the detector. In order to overcome this problem, we have started to implement the ORNL/UTK⁶ library of high-energy nuclear collision codes on ORNL's Intel/i860 hypercube.

This parallel computer is especially well suited for running large-scale Monte Carlo calculations, since each node can independently generate events. Asymptotically, speeds of 10 times a CRAY Y-MP can be expected when the full 128 node hypercube is utilized, but in order to get anywhere near that asymptotic value, major restructuring of the MC code framework⁶ was necessary.

In the development of the structure shown in Fig. 3.7, two main principles have been used as guidelines: (a) implementation of new Monte Carlo codes should be done with a minimum of change from the serial computer version, and (b) memory consumption should be distributed in order to run as large codes as possible. One node serves as a manager, which controls the generation of events and the flow

of data through the cube. The actual Monte Carlo code, like FRITIOF,⁷ runs on a set of generator nodes. The event output from each generator is sent to the interfacers, which changes the particle list from a code-dependent format to a universal format.⁶ The output from the interfacers is then sent to a set of analyzer nodes, which will analyze the generated events. Specifically, the analyzers can run GEANT or any other CERNLIB software package. The distinction between generator and analyzer nodes allows us to run large programs like FRITIOF and GEANT on separate cpu's and thereby increase the size of each code, which is needed in order to handle the large number of particles generated by the Monte Carlo codes for RHIC collisions.

Currently, algorithms for effective implementation of the proper load balancing between the three different types of nodes are being investigated.

As an additional utilization of the Intel hypercube, the analytical energy density model⁸ has been implemented. The serial computer version of this model has been troubled with numerical accuracy problems in evaluating four-dimensional space-time integrals over the collision zone. These problems have now been solved by brute force on the hypercube due to the speed-up factor of between 100 to 1000, as compared to the VAX implementation of the program.

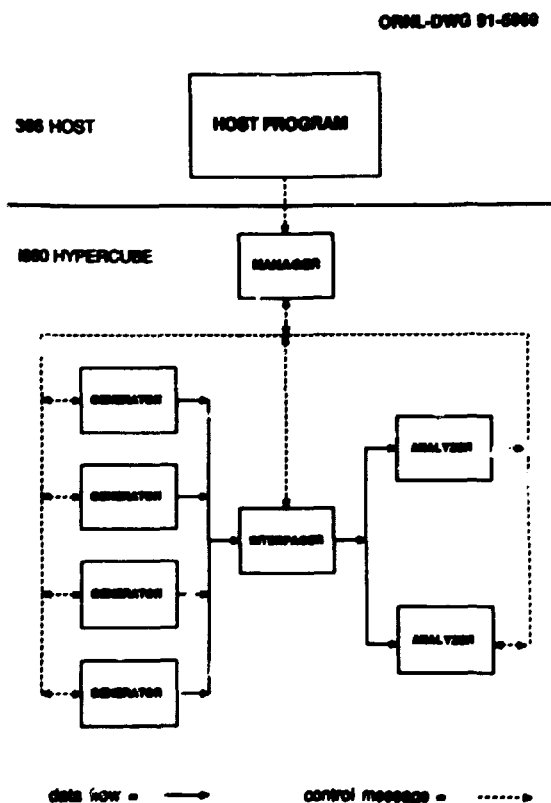


Fig. 3.7. Schematic illustration of the current structure of the ORNL/UTK high-energy nuclear collision Monte Carlo code implementation on the Intel/i860 hypercube.

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**LETTER OF INTENT
FOR A DIMUON SPECTROMETER
FOR RHIC MEASUREMENTS OF MUON
PAIRS, VECTOR MESONS, AND
PHOTONS**

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A letter of intent has been submitted to Brookhaven National Laboratory, stating our intent to construct an experiment to be used at the Relativistic Heavy Ion Collider (RHIC). The primary goal of the intended experiment is the observation of the quark-gluon plasma (QGP) expected to be formed in nucleus-nucleus collisions at RHIC energies. It is generally accepted that the best techniques by which the formation and the properties of the QGP can be investigated involve measurements of lepton pairs (virtual photons) and real photons which are emitted from the plasma and not likely to undergo subsequent interactions during the hadronization phase, and the heavier vector mesons (ϕ , J/ψ , Ψ , Ψ') which are formed of quarks and antiquarks that are not abundant in cold nuclei. Thus, the experiment will concentrate on measurements of cross sections for muon pairs, vector mesons, and direct photons. In addition, we also intend to measure global event parameters such as $dN/d\eta d\phi$ in order to classify

events by centrality; we plan to extract absolute cross sections by good luminosity monitoring. We will emphasize extensive kinematical coverage with a broad reach in both rapidity and transverse momentum. The experiment will be designed to operate at the maximum attainable RHIC luminosity. At forward rapidities, $|\eta| > 1.5$, observation of muon pairs appears to be a feasible way of dealing with the sharp rise in $dN/d\Omega$. We, thus, intend to construct a muon-pair spectrometer to cover angles down to 5 degrees. At midrapidity, we will measure muon pairs for large masses, $M_{\mu\mu} \leq 3 \text{ GeV}/c^2$; and at forward rapidities, we will extend our coverage down to a mass of 0.7 GeV. In addition, a specialized port spectrometer of limited polar and azimuthal coverage will be proposed for the observation of, e.g., the ϕ vector mesons by means of their hadronic decay branch and for the direct photon measurements.

We will use this detector to study both $p + A$ and $A + A$ reactions. It is expected that collisions of very heavy nuclei will result in the highest probability for quark-gluon plasma formation. The detector will be able to take advantage of all possible heavy-ion beams produced by RHIC. RHIC will be the only accelerator where it will be possible to study $p + A$ phenomena at high Q^2 and low x . Studies of these $p + A$ phenomena are important to help us understand phenomena observed in $A + B$ collisions and are also of interest in their own right since they relate to the behavior of partons in heavy nuclei and enable us to make the connection to regimes that can be described by perturbative QCD.

We propose a broad program of studies of muon-pair, vector-meson resonance and direct-photon production in $p + A$ and $A + B$ collisions. The various beam types and energies that will be available at RHIC will allow us to study carefully the dependence on A and $\sqrt{s}$, as well as on the kinematic variables, y and p_T . The knowledge gained will help us distinguish QGP formation from basic hadronic interactions. The implementation of our program will require the availability of a broad range of projectiles and of center-of-mass energies. The probability of forming a plasma and the proper time it exists before hadronization are expected to depend on $\sqrt{s}$. The various suppression mechanisms, e.g., J/ψ suppression, require a sampling of conditions over widely varying energy densities to establish their existence. This is also most easily achieved by varying $\sqrt{s}$. The relative importance of the production of thermal lepton pairs from a quark-gluon plasma vs production from a very hot hadronic gas is also expected to depend on $\sqrt{s}$. Finally, varying $\sqrt{s}$ will also change the x_F range we cover, which will allow

a broader range of relative momenta to be sampled for the partons producing the lepton pairs and vector mesons.

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CALORIMETER/ABSORBER OPTIMIZATION FOR A RHIC DIMUON EXPERIMENT

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G. R. Young

The purpose of the present work is to obtain basic information about backgrounds involved in a dimuon experiment and to determine the feasibility of such a measurement.⁷ The goal of a RHIC dimuon experiment is to detect dimuons over a reasonably broad range of masses and transverse momenta, p_T , that are in the correct range for detecting and diagnosing a quark-gluon plasma. The relevant kinematical regime is quite different from that studied in $\mu^+ - \mu^-$ experiments at large p-p colliders. Conclusions from recent theoretical considerations show that the region of greatest interest will be centered on the intermediate-mass region ($E \leq 5$ GeV) and that a broad p_T acceptance, from $p_T = 0$ up to $p_T = 5$ GeV/c, is essential.

There is some information in the literature concerning punch-through probabilities for incident hadrons in the range of 5 to 150 GeV/c.⁸ Most of the

data are for pions and protons incident on either steel or tungsten. These measurements are not detailed enough to be of value to our program. Most measurements were made for a range of absorber thicknesses, but mostly greater than 5 interaction lengths. For a RHIC dimuon detector absorbers of thickness less than 5 interaction lengths must be considered, particularly for $\gamma < 2$. Absorbers of mean Z , much less than that of steel, must be investigated. In addition, information on shower leakage for incident hadrons of $E < 5$ GeV is needed, since such incident particles far and away dominate the spectrum at RHIC.

The initial setup which we have prepared to investigate the background behind a hadron calorimeter/absorber seeks to answer the following questions: (a) What are the punch-through probabilities for pions, kaons, and protons with incident momenta in the range of 0.5 to 10 GeV/c striking a specific absorber? (b) How do these probabilities vary as a function of the absorber composition, e.g., carbon, aluminum, concrete or marble, steel, lead, when interleaved with a second material which is suitable active material for a sampling calorimeter? How do the results vary with absorber thickness? (c) What fraction of the exiting particles can penetrate a second shield and cause a "muon" trigger? How many of the punch-through particles will be rejected by position and angle cuts appropriate to a muon-finding analysis program?

Tests are being made with a steel-scintillator sandwich absorber/calorimeter. Further tests will be made, varying the inert absorber/scintillator thickness ratio and the type of inert absorber (steel, carbon, aluminum, lead). These studies will indicate whether the Monte Carlo calculations, which are being made using GEANT or CALOR, provide reliable first-order estimates of the leakage and whether a dimuon measurement is technically feasible at RHIC. (See "A Monte Carlo Study of π^- Incident on the RD-10 Calorimeter," this report.) We have installed the absorber/calorimeter in the A2 beam line at the Brookhaven National Laboratory accelerator (AGS). The absorber/calorimeter is constructed from 120 cm x 120 cm x 1.27 cm steel plates and 1-centimeter-thick plastic scintillator. The design consists of 11 slats, each 120 cm x 10 cm x 1 m, with photomultiplier readout on each end. The strips are stacked along their 120-cm sides, forming, in effect, a hodoscope between two sheets of steel. Sixteen such "slat arrays" have been installed, with alternating x- and y-orientation. Two are placed at the downstream end of the absorber/calorimeter to give hit information as the shower secondaries leave the stack. Successive slat arrays are rotated by 90° with

respect to each other. The first program of measurements will be completed with the array as it is presently set up. All of the slit arrays have been calibrated in beam before being installed. The total length of the assembly is variable, to a maximum of 3 meters. The support frame ensures that the plates and scintillator are kept in tight compression to avoid air gaps. This structure was developed to keep the cost of the readout to a minimum while providing periodic information on the transverse profile of the shower in addition to information on the depth at which the shower starts. Even with this arrangement, the structure requires 352 photomultipliers and ADC channels. This will increase to 652 channels when all the scintillator is installed. The absorber/calorimeters presently read out by using a LeCroy 2280 ADC system borrowed from CERN experiment WA80.

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7. *Proceedings of the Second RHIC Workshop*, May 25-29, 1987, Lawrence Berkeley Laboratory Report, LBL-24604.
8. R. Leuchs, "Measurement of the Hadronic Background in the Identification of Muons" (UA1 muon background tests), Diploma Thesis, RWTH Aachen, October 1982 (in German; English translation, ORNL/TR-88/31).

A MONTE CARLO STUDY OF π^- INCIDENT ON THE RD-10 CALORIMETER

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In order to estimate the hadronic and electromagnetic performance of the RD-10 calorimeter, a study of energy deposition and particle leakage has been conducted on a simulated sampling calorimeter of the same design dimensions and materials. The GEANT313 Monte Carlo program was used to study where hadronic showers start and how they develop. The determination of energies, multiplicities and radial distributions of particles that exit the back of the calorimeter as a function of incident energy is the primary goal of this investigation. Data for twelve cases were obtained for each incident particle momentum, 3, 5, 8, and 10 GeV/c, and calorimeter thickness, 4, 7, or 9 interaction lengths (λ). In each of the cases, 1000 incident π^- particles passed into the calorimeter one at a time at the center of its face, with completely longitudinal momentum. As an incident π^- continued its stepwise trajectory, it reacted with the detector material according to probabilities based on its and the material's properties. The actual materials of scintillating plastic and steel were approximated here with characteristics of Lucite and iron. Generated data include positions of the first hadronic shower vertex along the longitudinal axis of the calorimeter; positions and amounts of energy deposited throughout the calorimeter; and radial distributions, energy spectra, and multiplicities of charged particles, muons specifically, and massive neutral particles which exit the back face of the calorimeter. The total energy deposited per incident particle in the scintillator arrays and absorber layers was summed throughout each run, and all generated data are normalized per incident particle. Figure 3.8 shows the first hadronic shower vertex distributions for 5- and 10-GeV/c π^- incident particles. Binning of these vertex positions was based upon which scintillator

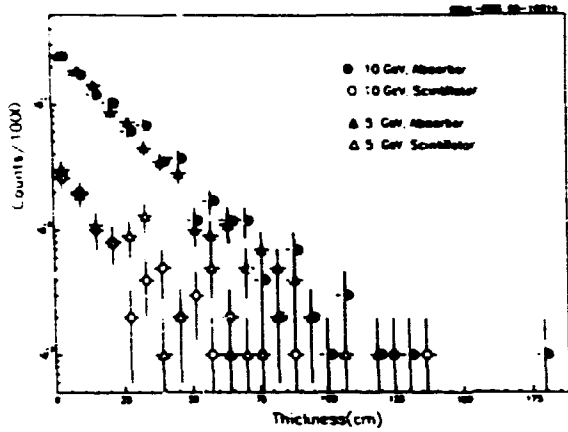


Fig. 3.8. Comparison of the first hadronic shower vertex position of 5- and 10-GeV/c π^- incident on the RD-10 calorimeter extended to 9λ .

array or absorber plate the reaction occurred in, so that a more clear presentation of the individual effects of scintillator and absorber could be made. The position uncertainty, shown here as 6.08 cm, is actually 1.00 cm for scintillator array positions and 5.08 cm for absorber plate positions, corresponding to their design thicknesses. Figures 3.9 and 3.10 show, respectively, the energy spectra and radial distributions of all charged particles which exit the calorimeter of 4λ thickness for 5- and 10-GeV/c incident π^- .

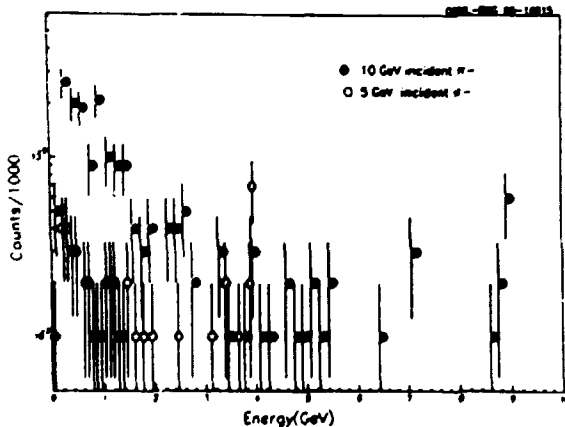


Fig. 3.9. Comparison of energy spectra of all charged particles which exit the RD-10 calorimeter at 4λ for 5- and 10-GeV/c incident π^- momentum.

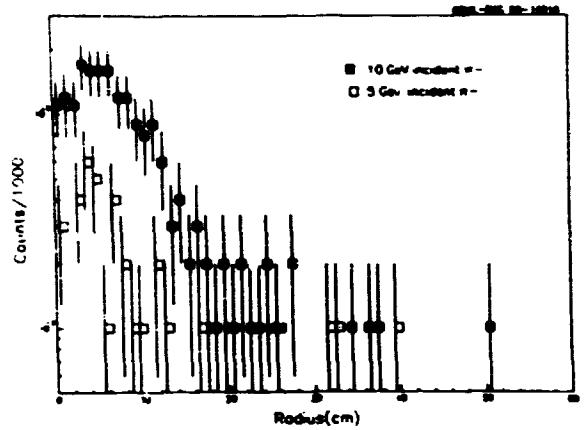


Fig. 3.10. Comparison of radial distributions of all charged particles which exit the RD-10 calorimeter at 4λ for 5 and 10 GeV/c incident π^- momentum.

-
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MONTE CARLO SIMULATIONS FOR DESIGNING THE INNER ABSORBER FOR THE RHIC DIMUON DETECTOR

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The only way of identifying muons in a high multiplicity environment of hadrons at RHIC requires that muon candidates penetrate an absorber of sufficient thickness to make the probability that a candidate is a hadron of the order of 10^{-4} or smaller. The thickness required must be less than the range of the lowest energy muons of interest, which puts a restriction on the dynamic range of the experiment. Multiple Coulomb scattering (MCS) and energy straggling (ES) in the absorber alter the momentum vector of the muons before they can be measured by the tracking system outside the absorber. To minimize these effects, one splits the required thickness of the absorber into two parts, the inner and the outer absorber. The purpose of the inner absorber is to reduce the large multiplicity of particles produced in central collisions to a level where tracking is feasible, while allowing the muons of interest to reach the tracking system. A critical background in the experiment is the muons from the decay of pions and kaons before they interact in the absorber. This can be reduced by choosing an absorber material with a short interaction length λ , which also makes the whole detector more compact and saves cost. From the above considerations, the absorber material best suited for this purpose will have low Z to minimize MCS, ES, and energy loss, and yet have a high density (small λ) to lower the decay background and the absorber size. Two possibilities under consideration are boron carbide (B_4C) and alumina (Al_2O_3) whose properties are compared in Table 3.1 to more conventional absorber materials.

Table 3.1. Properties of absorber materials

	(Z)	ρ (g/cm ³)	X_0 (cm)	λ (cm)	(p_T) _{MCS} ^a (MeV/c) λ	(Δx) _{MCS} ^b (cm)	$\Delta E/\lambda$ ^c (MeV) λ	τ_π/λ ^d
Be	4	1.85	35.3	40.7	15	0.31	130	19.2
B_4C	5.2	2.52	19.9	32.6	18	0.30	148	23.9
C	6	2.25	18.9	37.2	20	0.38	160	21.0
Al_2O_3	10	3.97	7.0	24.9	28	0.35	176	31.4
Al	13	2.70	8.9	39.4	32	0.63	186	19.8
Fe	26	7.87	1.76	16.7	49	0.40	209	46.8
Cu	29	8.96	1.44	15.2	52	0.39	217	51.3
W	74	19.3	0.35	9.6	87	0.42	247	81.3
Pb	82	11.35	0.56	16.9	92	0.77	253	46.2

a. Mean transverse momentum kick from MCS per λ .

b. Mean transverse displacement of 2-GeV muon from MCS per λ ;

c. Mean energy loss of 2-GeV muon per λ .

d. Ratio of pion decay length τ_π to interaction length λ .

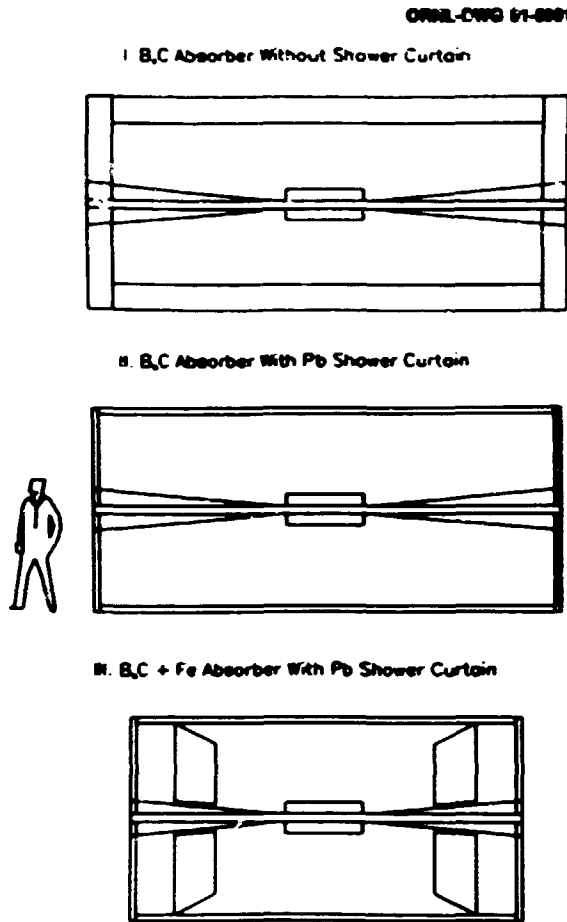


Fig. 3.11. Cut view of the three configurations of the inner absorber simulated in the present work.

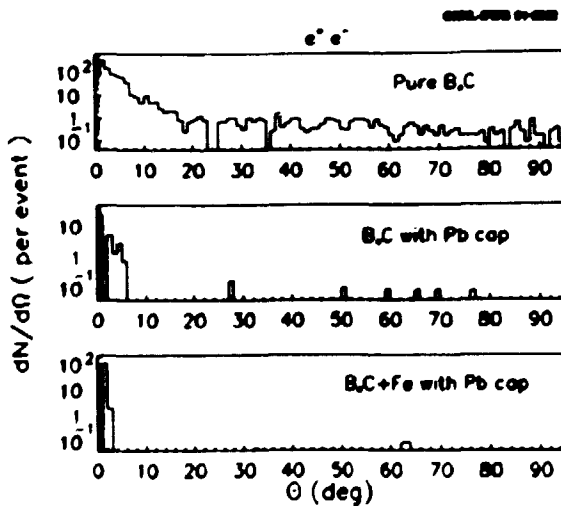


Fig. 3.12. Comparison of the e^+e^- leakage from the three configurations.

GEANT, the detector simulation package from CERN, was used to simulate particle leakage behind various configurations of the inner absorber. The simulations shot particles from central $\sqrt{s}/A = 200$ -GeV Au + Au HUET events into a cylindrical absorber of radius 4.5λ , and half length 10λ , with an open cavity in the center of 20-cm radius and 50-cm half length. A 0.1-cm-thick aluminum beam pipe of radius 5.0 cm passed along the axis of the cylinder. A 5° conical section of the absorber in the end-cap regions was replaced with air. A cut view of this geometry is shown in the top panel of Fig. 3.11. For a pure B_4C absorber, the particle leakage is dominated by gammas, e^+ , and e^- . The total charged-particle leakage per event predicted by GEANT is 150 in each of the end-cap regions (5 - 30°), and 280 in the barrel region (30 - 150°). This high flux is unacceptable for tracking chambers. A 0.5λ -thick Pb cap all around the absorber (shower curtain, see middle panel of Fig. 3.11) nearly eliminates the gamma and the e^+e^- leakage (Fig. 3.12) and softens very much the spectrum of the exiting gammas and e^+e^- (Fig. 3.13). In this case, the total charged-particle leakage per HUET event is 13 in each of the end-cap regions and 12 in the barrel region. We also carried out simulations using a graded absorber in the end-cap region, e.g., a combination of B_4C (5λ), Fe (4.5λ), and a Pb shower curtain (0.5λ) (lower panel of Fig. 3.11). This produces even better results since it not only removes gammas, e^+ , and e^- almost completely, but also reduces the background from (n,p) reactions considerably.

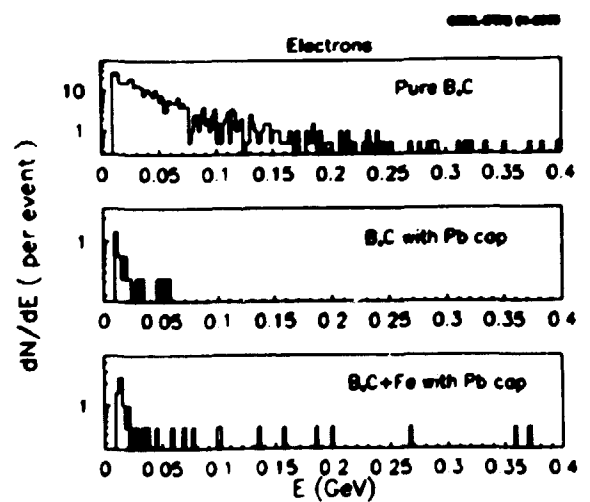


Fig. 3.13. Comparison of the energy spectrum of the e^+ and e^- leaking from the three configurations.

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RAPIDITIES OF PRODUCED PARTICLES IN 200-GeV/c $\pi^+/\text{p}/\text{K}^+$ INTERACTIONS ON Au, Ag, AND Mg¹

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<i>B. Cole</i> ⁶	<i>E. L. Koller</i> ¹⁰
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<i>T. A. Fuess</i> ⁶	<i>J. Grunhaus</i> ¹¹
<i>L. Grodzins</i> ⁶	<i>A. Levy</i> ¹¹
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<i>I. A. Pless</i> ⁶	<i>H. Yuta</i> ¹³
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We have used the Fermilab 30-in. bubble chamber-hybrid spectrometer to study the rapidities of "produced particles" in the interactions of 200-GeV/c protons and π^+ and K^+ mesons with nuclei of gold, silver, and magnesium. The average rapidity decreases linearly with the number of projectile collisions v_p (up to $v_p = 5$) with no A dependence and little beam dependence. The ratio R of normalized rapidity distributions for hadron-nucleus to hadron-proton interactions shows a plateau in the central region and becomes much larger in the target region. However, the increase is significantly less than has been reported in previous experiments. As a function of v_p , the ratio R rises linearly in the target region, more gently in the central region, and decreases slowly in the projectile region. Long-range rapidity correlations are observed in hadron-nucleus events, but not in hadron-proton events. For the former, it is shown that the correlations exist only for those events with multiple projectile collisions, as expected in the multichain dual parton model.

1. Abstract of published paper: *Phys. Rev. D* 41, 765 (Feb. 1990).
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**CHARGE-EXCHANGE
PHOTOPRODUCTION OF THE $a_2^-(1320)$
IN ASSOCIATION WITH Δ^{++}
AT 19.3 GeV/c¹**

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We examine the negative 3π final state produced in association with $\Delta^{++}(1232)$ in the reaction $\gamma p \rightarrow \Delta^{++}\pi^+\pi^-\pi^-$ at an incident energy of 19.3 GeV. The most prominent enhancement in the 3π spectrum occurs at a mass and with a width consistent with the parameters of the $a_2(1320)$. This identification is con-

firmed by the various angular distributions. The a_2 production cross section, corrected for efficiencies and alternate a_2 decay modes, is $0.45 \pm 0.05 \mu\text{b}$.

1. Abstract of published paper: *Phys. Rev. D* **41**, 3317 (June 1990).
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8. Birmingham Univ., Birmingham, England.
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14. MIT, Cambridge, MA.
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ORNL ACTIVITIES IN SUPPORT OF THE SSC L* COLLABORATION

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ORNL has joined the L* collaboration, which has proposed a detector for the Superconducting Super Collider. Effort has centered on the following:

1. Defining the role of the ORNL/UT team within the L* collaboration.
2. Assembling a multidisciplinary team dedicated to L* activities.
3. Establishing working relationships with various L* teams associated with common L* detector subsystems.
4. Participating in the writing of the L* "Expression of Interest," the L* "Letter of Intent," and several L*-related SSC detector subsystem R&D proposals.
5. Establishing a high-energy physics group in the Physics Division by expanding the current one-person activity.

The L* detector is shown in Fig. 3.14. ORNL, together with the Institute of Experimental and Theo-

retical Physics (ITEP) of Moscow, has the primary responsibility for the L* central hadron calorimeter. The first option for this subsystem is a sampling calorimeter with scintillator sampling (either solid tiles or liquid). The second option for the hadron calorimeter makes use of silicon detectors. This option can be implemented only if the current cost of silicon detectors is reduced by about an order of magnitude. ORNL is also involved in the barium fluoride electromagnetic calorimeter option (engineering and development of electronics) and in R&D dedicated to the identification of an optimum gas mixture needed for the operation of the muon chambers. All R&D subsystem proposals with which ORNL is associated have been approved, but the funding levels remain to be determined. In addition to the work on detector subsystems, ORNL has the overall responsibility for the SSC/L* "parameters and assembly" activity which includes system integration.

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3. Martin Marietta Energy Systems Engineering Division.
4. ORNL Health and Safety Research Division.
5. Consultant under subcontract from ITEP, Moscow.

ORNL-DWG 91-0000

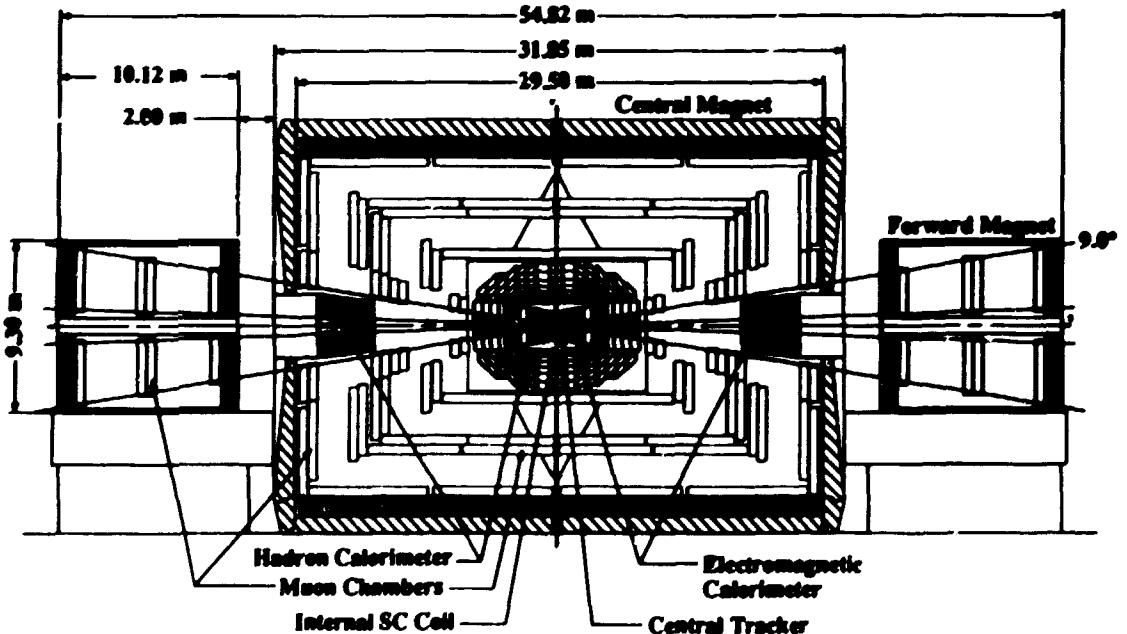


Fig. 3.14. L* detector.

4. THE UNISOR PROGRAM

The University Isotope Separator-Oak Ridge is a cooperative venture of universities, Oak Ridge Associated University, Oak Ridge National Laboratory, the U.S. Department of Energy, and the State of Tennessee. The primary purpose of the UNISOR consortium is to investigate the structures and decay mechanisms of rare, short-lived atomic nuclei which are prepared by means of a magnetic isotope separator coupled to the accelerators in the Holifield Heavy Ion Research Facility. The accounts which follow describe work at the UNISOR facility or work associated with UNISOR research performed principally by investigators outside the Physics Division. Research and development activities at UNISOR by Physics Division staff members are included in the Nuclear Physics Section.

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The prototype of the thermal ion source has been successfully used in two on-line tests and also in Experiment H289 at the HHIRF. During the experiment, the ion source was operated continuously for 56 hours without failure, producing ^{87}Rb with good yields. The principle usage for this source is for production of rare earth elements which will require considerably more power into the ion source. It is expected that the lifetime of the tungsten windows will be greatly reduced; therefore two additional sources are being constructed for these long rare earth experiments. On-line tests to compare the yields of this source with that of the FEBIAD-B2 plus carbon tetrachloride¹⁰ will be in early 1991 with on-line rare earth experiments starting soon afterward.

The Texas A&M laser beam line (collinear fast beam apparatus) has been installed on the UNISOR separator. This beam line is of modular design allowing for different components depending on the type of detection technique employed. Currently two different detection systems are being

examined. For signal detection at the same wavelength as the laser wavelength, an imaging system suppresses the strong stray light. For signal detection at a different wavelength, a large efficiency fiber optic array and light filters are used to advantage. As configured at present the beam line consists of sections containing Faraday cups, a beam scanner, deflection plates, a quadrupole lens, a charge exchange cell, photomultiplier detectors, and a tape transport-Faraday cup combination. In this system the frequency scanning is done by varying the potential of the charge exchange cell thus varying the Doppler shift. A personal computer system controls the voltage and records the detector counts. The beam line has been set up and separator beam transmission tests have been performed.

A prototype electronic module to control the advance of the tape in the UNISOR tape transport system has been built and tested. This device senses holes in the tape in order to determine the distance the tape is moved. This system eliminates completely the possibility that the source is not positioned correctly in front of the detectors.

Progress continues on the laser ion source project, although slowly because graduate student support is available only in the summer.

This year a much purer ^{67}Ga solution was evaporated in the helium jet apparatus at Mississippi State. It was found that 50% helium jet efficiency could still be achieved, and the resulting deposits were generally invisible. A SIMS depth profile of one of the samples indicated that the deposit was less than monolayer thick and that

the ^{67}Ga atoms were ~ 50 times more easily removed from the Ta surface than Ta atoms.

A new high-repetition rate (6000 Hz) copper vapor laser was used for the first time to ablate one of the helium jet samples at Colorado State. A high ablation efficiency ($>50\%$) was demonstrated. A peak at mass 67 was seen in the time-of-flight spectrum due to resonance ionization of ^{67}Ga atoms by a Nd:YAG-pumped dye laser at 30 Hz repetition rate. However, a quantitative measure of the ionization efficiency was not obtained ($\leq 50\%$ limit only) because the activity deposited on the detector at the end of the time-of-flight tube was not above background. This was due to the low activity of the initial sample and the difference in repetition rate of the lasers.

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10. H. K. Carter et al., *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1989*, ORNL 6578, p. 126.

DEVELOPMENTS AT UNISOR/NOF

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Recent developments at the UNISOR Nuclear Orientation Facility (UNISOR/NOF) have originated from discussions with Dr. Nick Stone, who was a summer visitor of the Joint Institute for Heavy Ion Research (JHIR). These developments include proposed methods for the measurement of the sign of the magnetic moment using beta scintillation techniques and the measurement of electric quadrupole moments for nuclides far from stability.

The determination of the sign of the nuclear magnetic moment is not possible from a standard measurement of the temperature dependence for a gamma-ray transition, since the gamma-ray anisotropy is dependent only on the even-terms of the orientation parameter, B_{λ} . Beta anisotropies, however, are dependent on the odd-terms of B_{λ} , and are therefore sensitive to the sign of the magnetic moment. The placement of plastic scintillator detectors outside the cryostat walls at 0° and 180° to the applied magnetic field would allow for the detection of beta asymmetries for nuclides far from stability at the UNISOR/NOF. In general, nuclides far from the stability line have beta decay energies that are high enough to pass through the outer cryostat walls of the dilution refrigerator. Use of the plastic scintillators would allow not only for the determination of the sign of the nuclear magnetic moment, but would also be available for the determination of the moments for $J = 1/2$ states. Our initial on-line test of this method revealed the necessity for stability with regard to the operation of the photomultiplier tubes; and future tests, possibly using an off-line source, are planned with improved detection equipment.

The value of the quadrupole moment is a direct measure of ground state nuclear deformation, and low-temperature nuclear orientation is a proven

technique for the measurement of these moments. Past measurements of the electric quadrupole moment using low-temperature nuclear orientation have all proceeded with room-temperature implantation and the subsequent top-loading of the nuclide of interest. Such procedures limit this technique to only those nuclides with long half-lives. The extension of this technique to short-lived activities can be made through the implementation of fully on-line quadrupole orientation, which we are in the process of developing at UNISOR/NOF.

The unique design of the bottom access for the UNISOR/NOF dilution refrigerator has led to complications in the attempt to use the electric field gradient (efg) of a Zn single crystal for electric quadrupole measurements because the efg would be perpendicular to all positions in the standard UNISOR/NOF detection configuration. A copper wedge having an angle of 45° was designed to allow for multiple angle detection. The wedge can be soldered to a standard cold finger, and allows for the detection of anisotropies at 15°, 45°, and 90°, without the appreciable attenuation of low-energy gamma rays, which must pass through a portion of the refrigerator cryostat in this new configuration. The initial fully on-line quadrupole moment measurement of the ground state in ¹²²I resulted in no anisotropies of any statistical significance and has given rise to questions regarding the possible changes of the beam position on the Zn crystal.

The authors appreciate the assistance of K. Farrell, Metals and Ceramics Division, in preparation of the Zn crystal.

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TESTING OF A SYMMETRICAL FOUR-DETECTOR COMPTON POLARIMETER USING LOW TEMPERATURE NUCLEAR ORIENTATION

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The theoretical value of linear polarization for a gamma transition with pure multipolarity is obtained with a simple expression⁵

$$p_{cal}(\pi/2) = \frac{\pm(3A_{22}H_2 - 7.5A_{44}H_4)}{(2 - A_{22} + 0.75A_{44})}$$

where +/- is taken for a transition without/with a parity change, and

$$A_{\lambda\lambda} = B_{\lambda}U_{\lambda}A_{\lambda}$$

where $B_{\lambda}A_{\lambda}$ and U_{λ} have their usual meanings.⁵ For a pure transition and $\lambda \leq 4$, $H_2 = 1$ and $H_4 = -1/6$. The calculated value of the degree of polarization is then compared to the experimental asymmetry of the polarimeter:⁵

$$\Delta = \frac{(N_{||}/N_{\perp})_{\omega} - (N_{||}/N_{\perp})_c}{(N_{||}/N_{\perp})_{\omega} + (N_{||}/N_{\perp})_c}$$

where ω stands for warm and c for cold data sets. $N_{||}/N_{\perp}$ are the full energy counting rate of the analyzer parallel/perpendicular to the plane defined by the orientation axis of the source and the direction of the linearly polarized radiation. This definition of Δ eliminates possible systematic errors arising either in half-life corrections or in the counting time of warm and cold measurements. For a four-detector Compton polarimeter, $N_{||} = ABcd + abCD$, $N_{\perp} = aCbD + acBD$, where paired capital letters indicate detector coincidences and paired lower case letters indicate detector anti-coincidence for each of the four full energy events, as in Ref 6.

The quantity Δ is related to the measured value of the degree of linear polarization P^{exp} by

$$P^{\text{exp}} = \Delta/Q$$

where Q is the polarization detection efficiency, and it is dependent on the energy of transition.

In the present experiment, Q was determined for a four-detector Compton polarimeter (of the same design as in Ref. 6, but using four Ge(Li) detectors with 12% efficiency) using the UNISOR/NOF ^3He - ^4He dilution refrigerator. Angular distributions of emitted gamma-rays from oriented $^{192}\text{IrFe}$, $^{54}\text{MnNi}$ and $^{60}\text{CoFe}$ samples were measured simultaneously at 180° and 270° relative to the direction of external applied magnetic field. The measured anisotropy of the distribution was used to determine an operation temperature (7.5 ± 0.5)mk. This value was used to calculate the B_λ coefficients for each of the samples. The U_λ 's were determined using the well-known level schemes for these nuclei and F_λ are tabulated in Ref. 7.

The experimental results indicate the excellent performance of the tested polarimeter. The polarization detection efficiency of the tested symmetrical four-detector polarimeter was compared with previously measured three-detector, and multisegment polarimeters⁵ have proved to have the best efficiency. Its design and quality makes it very suitable for use in both compact ball and low temperature nuclear orientation measurements.

HYPERFINE FIELDS MEASUREMENTS IN ALLOYS

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A measurement of the hyperfine field of the Heusler alloy Cu_2MnIn was attempted using the UNISOR Nuclear Orientation Facility (UNISOR/NOF). A sample of the alloy was formed into a small disk 10-mm diameter and 2-mm thick. Radioactive $^{114\text{m}}\text{In}$ ($t_{1/2} = 49.5$ d) was then diffused into the alloy at a temperature of 350°C under a hydrogen atmosphere. The sample was then soldered, along with a $^{57}\text{CoFe}$ nuclear orientation thermometer, onto the end of a copper cold finger and top-loaded into the He dilution refrigerator.

Temperature-dependence data were collected over a two-day period at angles of 0° , 90° , 180° , and 270° to the applied 1.0 T magnetic field. The $W(\theta)$ vs. temperature curves determined for the 190-keV E4 isomeric transition in ^{114}In allowed for the determination of the hyperfine field for the Z site in the Cu_2MnIn Heusler alloy. This measured field was significantly lower than the expected value as extrapolated from the known hyperfine fields in the Heusler alloys having Cd and Sn in the identical Z site.⁴ It is possible, however, that the radioactive indium dopant did not situate in the proper site in the diffusion process, leading to an erroneously small value of the hyperfine field. This hypothesis will be tested by an experiment which will repeat the measurement following a different diffusion process and corroborating the goodness of the sample using X-ray diffraction.

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5. J. Rikowska, N. J. Stone, and V. R. Green, *Nuc. Instr. Meth. A* **241**, 461 (1985).

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7. K. S. Krane, *Low Temperature Nuclear Orientation*, ed. N. J. Stone and H. Postma, North Holland (1986).

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NUCLEAR ORIENTATION OF ^{184}Au

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We are searching for evidence of shape coexistence in the E2/M1 multipole mixing ratios of transitions connecting co-existing bands in even-even nuclei in the mass 180-190 region. Simultaneously, improved knowledge of the E2/M1 ratios will permit unambiguous analysis of electron conversion data to obtain E0 multipoles, which also serves as a probe of the mixed bands.

The decay of ^{184}Au (53 s) is among the shortest-lived decays possible using nuclear orientation techniques, and represents a severe test of the new on-line refrigerator at UNISOR. We performed the orientation experiment in August 1989, implanting the activity into an Fe target at the UNISOR Nuclear Orientation Facility and observing the gamma rays with six detectors located in a symmetric configuration around the sample. The data were taken in the fully on-line mode at temperatures at or below 8 mk.

In preparation for the refrigerator run, approximately four shifts of spectroscopy data were taken. The level scheme of the ^{184}Pt daughter is not well established, and the lack of detailed knowledge of the decay scheme makes analysis of the nuclear orientation data difficult. We obtained the spectroscopy data consisting of gamma singles, electron singles, multiscale data and gamma-gamma and electron-gamma coincidence data. The analysis of those spectroscopy data has been completed. Over 40 new energy levels have been identified and assigned spin and parity. The decay scheme of ^{184}Pt has been updated. Some of the results will be further confirmed when the orientation data is finally analyzed.

There is accumulating evidence that the E0 component of a transition between levels of different bands can serve as the fingerprint for shape coexistence and shape mixing. The spectroscopy results show that transitions between levels of two distinct bands have a strong E0 component. Those two bands can be used to study the shape coexistence and mixing (Fig. 4.1). The analysis of orientation data is still under way, which will eventually help determine the E0 strength for those transitions.

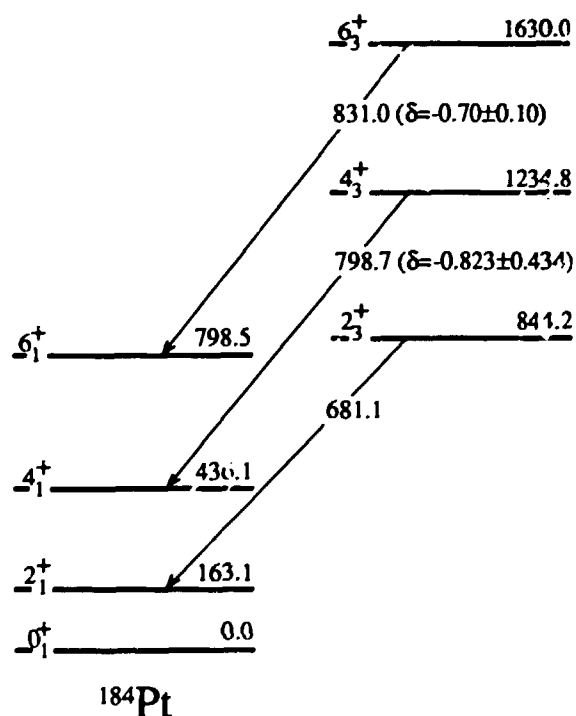


Fig. 4.1. Two coexisting bands with possible E0 transitions.

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NUCLEAR ORIENTATION OF ^{185}Au

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<i>M. O. Kortelahi</i> ⁴	<i>J. L. Wood</i> ⁹

As part of an overall plan to investigate the lighter mass, odd Au-Pt-Ir isotopes, on-line nuclear orientation was performed on ^{185}Au . The Au was produced by the reaction $^{12}\text{C}(^{181}\text{Ta}, 8n)$ and the mass separated activity was implanted into an Fe foil which was soldered to the cold-finger of the UNISOR/NOF ^3He - ^4He dilution refrigerator. Gamma radiations were observed at seven angles (relative to the magnetic field) for roughly six cold/warm cycles, and over 650 ten-minute spectra were recorded for each angle. The refrigerator was operated in the semi-online mode, i.e., using beam-off time to allow for the decay of Pt activity, and a temperature of around 11 mK was maintained during beam-on cycles. New sample holders were top loaded two times during the 108-hour run to remove the 14.4-hour iridium activity.

Several gamma-ray lines which were used to monitor the experiment indicated good orientation of each of the daughters. The 152.8-keV iridium line, for example, had an anisotropy of about 61 percent, and ($0^\circ/90^\circ$) count ratios of the 254.2-keV osmium line are illustrated in Fig. 4.2 for selected 10-minute cycles. This line shows a small but clearly distinguishable effect. Although analysis of the data has not been completed, relatively high count rates at zero degrees (around 25/s for the 243-keV Pt [100%] line) indicate that analysis of even the weaker (<1%) lines should be possible.

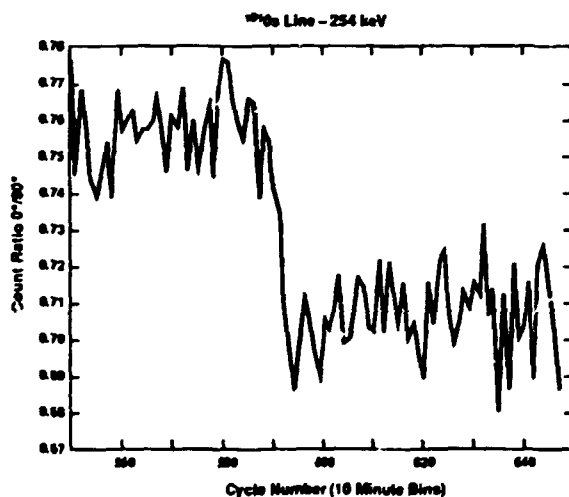


Fig. 4.2. Count ratio ($0^\circ/90^\circ$) of the 254.2-keV osmium line.

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NUCLEAR ORIENTATION OF ^{189}Au

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In order to avoid extra set-up and cooling time, the orientation of ^{189}Au was done immediately following the ^{185}Au run, as discussed in the previous paper. The separator was retuned for mass 189 and again the activity was implanted into an iron foil soldered onto the cold finger of the UNISOR/NOF ^3He - ^4He dilution refrigerator. Activity was collected at rates of about $4 \times 10^5/\text{s}$ for 25 hours (several cold, warm cycles) before the beam was removed. The 4°K baffle was then closed, allowing the fridge to cool to a base temperature of about 8mK , and over 260 10-minute spectra were recorded to observe the long-lived (10.9 hr) platinum decay. The 166.4-keV ($9/2^- - 5/2^-$) Pt line was monitored during beam-on cycles and an anisotropy of about 56% was observed (see Fig. 4.3). Several peaks were monitored during the decay period, and a plot of ($0^\circ/90^\circ$) count ratios for the 607.6-keV iridium line (Fig. 4.4) also shows good anisotropy.

Spectroscopy of the Pt-Ir decay was done in August 1989 in preparation for this experiment. Electron and gamma singles, time planes, and gamma-gamma and gamma-electron coincidence data have been analyzed. The spectroscopy is almost complete. Since information about the decay schemes was needed in order to calculate deorientation parameters before analysis of the orientation data could be finished, only preliminary analysis of the orientation data has been completed.

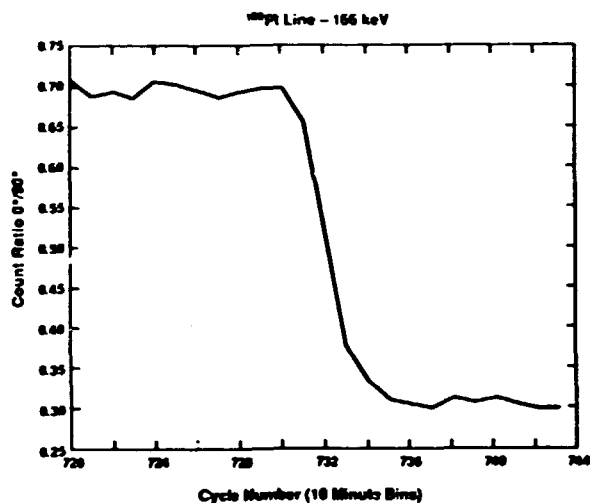


Fig. 4.3. Count ratio ($0^\circ/90^\circ$) of the ($9/2^- - 5/2^-$) 166 keV platinum line.

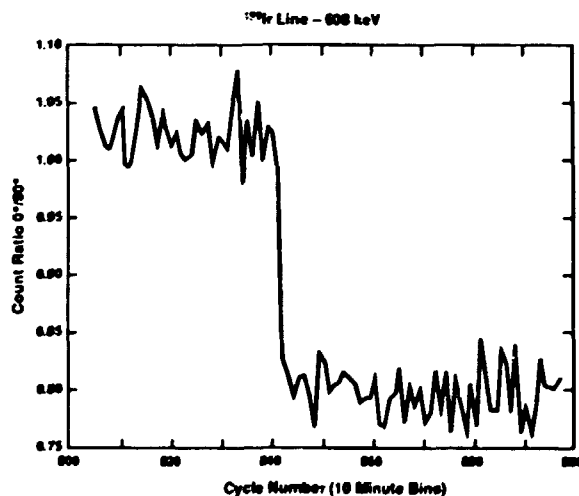


Fig. 4.4. Ratio of ($0^\circ/90^\circ$) counts of the 608 keV iridium line.

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ON-LINE NUCLEAR ORIENTATION OF ^{187m}Hg

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As part of the program to investigate odd-mass nuclei in the $Z \leq 82$ region which show E0 enhanced transitions between shape coexisting configurations,¹⁰ we have performed on-line nuclear orientation (OLNO) of the ^{187m}Hg decay in an attempt to measure the distribution of ^{187}Au transition γ -rays in aligned ^{187}Au and from that information to determine the multipole mixing ratios of the interband transitions. This was performed at the UNISOR on-line nuclear orientation facility where the separated ^{187m}Hg activity was implanted on-line into an Fe foil at 10.9 mK in a magnetic field of 83.8 T. A six-detector experiment was performed in March 1990 using the $^{176}\text{Hf}(^{16}\text{O}, 5n)^{187}\text{Hg}$ reaction. In October 1990, an eight-detector experiment, using the reaction $^{181}\text{W}(^{12}\text{C}, xn)^{187}\text{Hg}$, was cut short after 15 hours due to equipment failure, but nonetheless yielded excellent data.

The OLNO measurements on these odd mass nuclei are the most formidable nuclear orientation experiments ever attempted and are probing the limits of the experimental feasibility of obtaining accurate multipole mixing ratios of weak and/or highly converted transitions in complex nuclear decays. The massive quantities of data obtained are being organized and the myriad of corrections (dead time, pileup, etc.) are being determined and applied. Several lines have been analyzed in order to ascertain the quality of the data. For example, the M1,E2 multipole mixing of the 220.7-keV transition in ^{187}Au was determined to be $67 \pm 3\%$ E2. The analysis of many other transitions is currently under way.

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SEARCH FOR SUPERDEFORMATION IN ^{192}Hg

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Superdeformation at low-spin (0^+) has been predicted in the neutron-deficient Pt, Hg, and Pb region,⁷ and superdeformed states have been discovered^{8,9} through in-beam reactions in several Hg isotopes with the bands identified (indirectly) down to about 8^+ . The band heads and lower-spin members of these bands have not been observed, nor have the connection between the superformed structures and the ground-state been found. In fact, this inability of in-beam reaction spectroscopy to locate (energy) the superdeformed structures is a common problem, and only in ^{135}Nd has the superdeformed band been connected¹⁰ to states for which the decay path is known.

We performed a 12-shift experiment, in August 1990, to search for superdeformed states in ^{192}Hg with $I \leq 8$ by studying the excited states of ^{192}Hg populated in the β^+ decay of $^{192\text{m},8\text{Tl}}$ (10.8 m, 7^+ and 9.4 m, 2^- respectively). The β^+ decay of the $J = 7^+$ isomer in ^{192}Tl is known¹¹ to populate states in ^{192}Hg with $J \leq 9$. Since Q_{β^+} is 6.4 ± 0.2 MeV for the $^{192\text{m},8\text{Tl}} \rightarrow ^{192}\text{Hg}$ decay, and since the superdeformed bandhead is expected⁷ to lie in the 3.5-MeV range, there are no energy or angular momentum restrictions on the population of this superdeformed structure via β^+ decay. Other unknown hindrances may, of course, be operative.

Since coexisting bands in this region are, without exception, observed¹² to decay by strong E0 transitions, it was decided that in addition to e- γ , γ - γ and α - γ coincidence, it would be essential to also perform e-e and α -e coincidence measurements. To accomplish this, a vertical electron spectrometer was constructed which enabled one

to perform e-e, γ -e, α -e coincidence spectroscopy at a single station on the UNISOR isotope separator.

A total of 2.2×10^7 e-e, 3.9×10^7 e- γ , and 1.1×10^8 γ - γ events were obtained. No events involving α -particles were observed. Preliminary analysis of the data reveal that if the superdeformed structure is populated in the $^{192\text{m},8\text{Tl}}$ decay the population intensity is less than 1%. We have shown¹² in ^{190}Hg that coexisting bands with populations <1% can indeed be located (energy) and quantified (spin, parity) with meticulous analysis of the data. That type of analysis on the ^{192}Hg data is currently under way.

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SEARCH FOR A SHAPE ISOMER IN ^{194}Hg POPULATED BY ^{194}Tl BETA DECAY

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Recent theoretical calculations (e.g., Bonche et al.,⁸) predict that nuclei in the vicinity of ^{194}Hg should possess shape isomers analogous to the fission isomers identified in the actinide nuclei. However, because the fission barriers of these nuclei is much higher than those of the actinide nuclei, the main decay mode of these shape isomers would be gamma-ray decay. Successful observation of shape isomers outside the actinide region would be important because it would validate theoretical concepts of the nuclear potential energy surface and provide an opportunity to study nuclei at high deformation but low spin.

We have begun an experimental program to search for and characterize shape isomers in the mercury nuclei. Candidates for study include nuclei where superdeformation at low spin has been observed. As a part of this program, we are studying the beta decay of ^{194}Tl to ^{194}Hg . The main objective of this experiment was to identify the E2 gamma-ray decay of the shape isomer to the first 2^+ level in ^{194}Hg . The second objective was to identify candidates for the lowest 1^- level in ^{194}Hg because we know from studies in U that the main gamma-ray decay branch can be either an E2 transition to the lowest 2^+ level or an E1 transition to the lowest 1^- levels.^{9,10}

The UNISOR on-line isotope separator at the Holifield Heavy Ion Research Facility (Oak Ridge National Laboratory) was used to produce the ^{194}Tl activity. The production reaction was $^{12}\text{C} + \text{Rc}$ at a bombarding energy of 90 MeV. The separator deposited the activity on a tape, which moved it from the deposition site to two successive detector stations. Bombardment and counting cycles were 180 s in duration.

The first detector station, where the data reported here were collected, consisted of two large

(efficiencies of 40% and 23%), thin-window, high-purity, germanium detectors oriented facing each other and associated electronics. The E2 decay mode for the shape isomer is expected to populate mainly the lowest 2^+ level at 428 keV. We used the projected spectrum coincident with 428-keV transition to obtain the intensity (in this case, an upper limit on the intensity) for a high-energy E2 transition out of the isomer. The absolute normalization for this intensity was made by using the known intensity of 749-keV transition, which is coincident with the 428-keV transition. The absolute limit obtained ranges from about 0.022% for a 3-MeV transition to about 0.003% for a 4.5-MeV transition.

We also obtained preliminary information on possible candidates for the first 1^- level in ^{194}Hg . No low-lying 1^- levels have been identified previously in the mercury nuclei.

We have identified 11 new levels below 2200 keV in ^{194}Hg , of which five are potential candidates for 1^- levels: 1502, 1959.9, 1980.0, 2069.4, and 2105.9 keV. Additional experiments emphasizing the decay of the low-spin ^{194}Tl isomer, in conjunction with conversion-electron or angular distribution spectroscopy, will be necessary to fully characterize these levels and to definitely establish a spin and parity of 1^- .

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DESCRIPTION OF RELATIVE γ -RAY INTENSITIES IN ^{193}Hg BY A PARTICLE + CORE COUPLING MODEL

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As discussed in the previous report,⁴ standard calculations have been made within the particle + triaxial rotor model for both the positive and negative parity states in ^{193}Hg . The goal of these calculations is to investigate how well the present data constrains the necessary parameters, and especially to see if there is any clear evidence for a triaxial nuclear shape.

These calculations are "standard" in the sense that virtually all of the parameters were set at their standard values, and were not adjusted to improve the fit with the data. Three different nuclear shapes were considered: prolate, oblate, and an "oblatish" triaxial shape. The latter (triaxial) shape was clearly preferred in previous calculations for ^{195}Tl , and is expected to be appropriate also for the effective core for ^{193}Hg . The previous report⁴ compared calculations with the low energy level spectrum and the known bandhead moments for both the positive and negative parity states. These calculations clearly exclude the prolate shape, but the oblate and triaxial shapes give very similar results at excitation energies below 800 keV.

A more sensitive test might be provided by the electromagnetic transition matrix elements, and a comparison between the experimental and calculated relative transition rates (gamma-ray intensities) has been made. For the low-lying positive parity states, the calculated relative intensities are very similar for the two shapes considered (triaxial and oblate), and both agree reasonably well with the data. The experimental and calculated relative gamma-ray intensities for the negative parity states below 700 keV are shown in Table 4.1. Not included in the comparison are the $9/2^-$ state at 635 keV, the $5/2^-$ (40 keV), and $1/2^-$ state (50 keV). In these cases, only one transition is observed to depopulate the level, and is consistent with both the oblate and triaxial calculations. The

comparison of the relative intensities clearly favors the triaxial shape calculations. In particular, note the very good agreement between the data and the triaxial shape for the decay patterns of the second and third $5/2^-$ states, and the strong disagreement with the oblate shape for these same states.

Overall, there is strong evidence of non-axial shapes in the low-energy structure of ^{193}Hg . The agreement between the particle + triaxial rotor model and the data is especially impressive considering that these are "standard" calculations and no fine-tuning of parameters was made.

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Table 4.1. Relative gamma-ray intensities between negative parity states in ^{193}Hg compared with particle + triaxial rotor calculations.

Transition	Theoretical		Exp't
	Triax.	Oblate	
$(3/2^-)_1 \rightarrow 3/2^-$	100	100	100
$\rightarrow 5/2^-$	16	43	24
$\rightarrow 1/2^-$	14	53	14
$(5/2^-)_1 \rightarrow 3/2^-$	100	73	100
$\rightarrow 5/2^-$	3	67	1
$\rightarrow 1/2^-$	11	100	11
$\rightarrow (3/2^-)_2$	0.2	0.2	0.3
$(5/2^-)_2 \rightarrow 3/2^-$	51	100	36
$\rightarrow 5/2^-$	100	67	100
$\rightarrow 1/2^-$	41	0.3	26
$\rightarrow (3/2^-)_1$	0	1	-
$7/2^- \rightarrow 3/2^-$	8	6	13
$\rightarrow 5/2^-$	100	100	100
$(1/2^-)_1 \rightarrow 3/2^-$	100	100	100
$\rightarrow 5/2^-$	10	0.6	17
$\rightarrow 1/2^-$	5	8	2
$\rightarrow (3/2^-)_2$	0.6	0.2	-
$(3/2^-)_2 \rightarrow 3/2^-$	100	100	100
$\rightarrow 5/2^-$	66	10	61
$\rightarrow 1/2^-$	21	26	7
$\rightarrow (3/2^-)_1$	3	9	-
$\rightarrow (5/2^-)_1$	20	21	2

α -DECAY RATES FOR LIGHT AU ISOTOPES

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Because of our interest in co-existing shapes of nuclei in this region we recently studied the α -decay of mass 181-186 sources produced with the use of the University Isotope Separator at Oak Ridge (UNISOR) on-line at the Holifield Heavy-Ion Research Facility. Observed α activities were identified via decay time and α -X ray coincidences. Coincidence measurements established several low-lying levels in the $^{177,178,179,180}\text{Ir}$.

The energies, relative intensities, and hindrance factors of the α groups observed in the decay of the six isotopes of Au in this work are given in Table 4.2. The error on the α energies is estimated to be about ± 5 keV and for the peaks that were observed in earlier work agree within the estimated error.^{8,9,10} With the exception of ^{182}Au , the half-lives agree well with previous measurements. The half-life deduced for ^{182}Au α decay is 13 ± 2 s, which is somewhat smaller than the result of Hagberg et al.⁸ By using standard techniques, branching ratios and hindrance factors were deduced for each α group. The results of our measurements and analysis are summarized in Table 4.2.

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Table 4.2. Energies, branches, relative intensities, and hindrance factors for the observed α lines.

Isotope (Branch(%))	E_{α} (keV)	Relative I_{α}	HF
^{181}Au (1.3 ± 0.2)	5301	0.6	46
	5364	9.1	6.2
	5407	5.6	16
	5479	100.0	1.9
	5545	5.9	67
	5581	5.1	114
^{182}Au (0.13 ± 0.05)	5626	96.8	9.7
	5283	9.8	16
	5352	100.0	3.3
	5403	28.8	21
^{183}Au (0.78 ± 0.24)	4964	0.2	6
	5084	0.4	16
	5160	0.6	25
	5349	100.0	1.4
^{184}Au (0.013 ± 0.003)	4980	23.0	7.7
	5024	22.3	14
	5065	14.1	40
	5109	100.0	8.9
^{185}Au (0.62 ± 0.1)	5187	54.7	40
	5069	100.0	0.4
^{186}Au (0.0009 ± 0.0001)	4826	0.16	9.6
	4656	100.0	1.1

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IDENTIFICATION OF ^{185}Pt α ACTIVITY

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While the α -decay of Pt in the mass range between 168 and 184 has been studied previously, the α -decay of ^{185}Pt has never been reported.⁸ As a part of a systematic study of α decay in this region, we recently observed the decay of mass 185 sources produced by the $^{181}\text{Ta}(^{12}\text{C}, 8n)$ reaction. The mass 185 beam from the separator was directed onto the UNISOR tape collector system. After an 8-min deposition, the collected source was moved to the first of two counting stations where a cooled Si(Li) detector was used to observe α particles and electrons and a Ge(Li) detector was used to observe γ and X rays. At the same time, the old source was moved to station 2 where a Si(Au) surface barrier detector was utilized to measure α -particles, and two Ge(Li) detectors were used to observe γ and X rays. All of the detectors were calibrated with standard sources.

Spectrum multiscaling was used to determine the decay times and absolute intensity of each γ , α , e^- , and X-ray line observed. In addition, γ - γ , α - γ , and e - γ coincidence data were accumulated; however, no α - γ coincidences were observed for $A = 185$ sources.

The α -particle spectrum for mass 185 contained three peaks. The half-life measured for the 5069- and 4826-keV peaks is consistent with the known half-life for ^{185}Au .⁸ There are two long-lived states⁸ of ^{185}Pt : (1) the ground state with an I^π of $(9/2^+)$ and a half-life of 70.9 min and (2) the first excited state with an I^π of $(1/2^-)$ and a half-life of 33.0 min. The intensity of the 4444-keV peak increased during the measurement in a way that is consistent with the feeding of either of these isomers by the ec/β^+ decay of ^{185}Au .

Prior, rather complete, construction of schemes for ec/β^+ decay of ^{185}Pt (Ref. 9) enabled our

estimation of α /total branching ratios from the present data. The calculation of the branching for the ^{185}Pt α was complicated by the fact that both the ^{185}Pt isomer and ground state produce γ -ray transitions in ^{185}Ir and also Ir X rays. Use of either X rays or γ rays to determine the number of ec/β^+ decays of the α -decaying state of ^{185}Pt thus required an evaluation of the decay scheme. We took the total intensity of γ rays and conversion electrons to the ground state of ^{185}Ir to be the total ec/β^+ intensity from both ^{185}Pt states and used information from previous decay scheme work to divide this intensity between the two decaying states. If the 4444-keV α comes from decay of the 33-min isomer, its branch is $1.0 \pm 0.4 \times 10^{-3}\%$; if it comes from the 70.9-min ground state, the branch is $5.0 \pm 2.0 \times 10^{-3}\%$. The Hindrance Factor¹⁰ for the decay of ^{185}Pt is 1.3 if the decay is from the 33-min isomer and 0.6 if from the 70.9-min ground state, indicating that the transition is not hindered and that the spin of the state populated in ^{181}Os is the same as that of ^{185}Pt . The observed Q -value in either case agrees with the prediction of 4596 ± 380 keV from nuclear mass systematics.¹¹

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THE SHAPE OF THE DEFORMED STATES IN THE LEAD ISOTOPES

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Three very-converted transitions have been found in ¹⁹⁵Pb populated in the radioactive decay of ¹⁹⁵Bi. These transitions have multipolarity E0 + M1 + E2 and define a deformed band with spin-parity (energy), 13/2⁺ (1093 keV), 9/2⁺ (1329 keV), and 11/2⁺ (1380 keV). This can be contrasted with the spherical *i*_{13/2} structure with 13/2⁺ (203 keV), 11/2⁺ (979 keV), 9/2⁺ (1011 keV). This deformed band closely resembles the *i*_{13/2} structure in ¹⁹³Hg with 13/2⁺ (141 keV), 9/2⁺ (349 keV), and 11/2⁺ (464 keV). The deformed band corresponds closely to that expected for a rotor with a deformation of $\beta = 0.12$.

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AN APPLICATION OF THE DDM TO TUNGSTEN NUCLEI

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The recent developments of the dynamic deformation model (DDM) and its superiority compared to its predecessor, the pairing plus quadrupole model, have recently been demonstrated in an application to tungsten nuclei.⁴ The quadrupole moments of the 2⁺_{gs} and 2⁺_γ states were calculated for the even-A tungsten isotopes, ¹⁸⁰⁻¹⁸⁶W. The values are not sensitive to single particle aspects but do give a description of collective effects. Mixing between the different K-components in levels was evaluated and, although the K = 0 component in the 2⁺_γ state was small, a substantial K = 2 component in the 2⁺_γ was found. These admixtures influence the quadrupole moments and branching ratios of E2 transitions linking the various bands. At high spin, we find that significant K = 4 admixtures are present.

Recently, Wu et al.⁵ measured branching ratios and quadrupole moments for ^{182,184}W. Agreement between the DDM predictions and the experimental data is generally good and, in particular, the failure of the pairing plus quadrupole model has been overcome by the DDM which gives good agreements for the sign and magnitude of Q-values. The measured E0 component⁶ in the 792-keV transition linking 2⁺ levels in the γ and ground-state bands in ¹⁸⁴W, $X(E0/E2) = 1.1(3) \times 10^{-3}$, also implies a significant K = 0 component in the γ-band, otherwise an E0 transition between these levels would be forbidden.

These values are determined largely by collective effects and not by the proton and neutron pairing strengths. Changing these has the effect of altering the level energies and improving the quality of the fit. We intend to extend the model calculation and to include a wider set of experimental data in a future development of this work.

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THE IDENTIFICATION OF MIXED-SYMMETRY STATES

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Mixed-symmetry states are designated as those states in which the neutrons' and protons' collective motions, or some part of these motions, are out of phase. In vibrational nuclei we can consider the neutrons and protons to be vibrating at the same frequency, but mutually perpendicular to each other, about their equilibrium shape.

States corresponding to this excitation mode have been identified in a number of nuclei² and a theoretical treatment has been fully developed.³ Several experiments have been undertaken at the on-line nuclear orientation facility at UNISOR to locate these states and to examine their decay modes. These data are presently being analyzed and several other experiments are scheduled for the coming year.

The lowest lying mixed-symmetry state in a vibrational nucleus is a 2^+ level, generally at about 2 MeV, which decays strongly to the first 2^+ level by a predominantly M1 transition. Besides this 2^+ m.s. level, we may expect a group of higher lying, low spin m.s. states; and it is important to identify these as additional tests of the model calculations.

Not all nuclei are expected to show these features strongly, although they are common to all collective excitations. In particular, the strength of

the M1 transition depends sensitively on the nuclear structure. The parameters which influence the decay characteristics have been examined for a wide range of N and Z values.⁴ The most favorable vibrational-like nuclei are those occurring immediately before the onset of deformation at $N = 88$ and before shell closures at $Z = 50$ and 82 . The UNISOR measurements, past and planned, are located around $Z = 78$ and for $N = 80$ isotones where we hope that the present model describes adequately the transitions. If so, this will allow a better understanding of the model parameters. Some experiments are also being undertaken in the $A = 70$ region which the analysis, reported in Ref. 4, indicates is unfavorable for the identification of m.s. states since the $B(M1)$ transition probability is suppressed. However, it is important to identify the m.s. states in this region and hence understand the nuclear structure features which depress the usual m.s. characteristics.

The sharing of mixed characteristics with regular states strongly influences the multipole components of the decay modes of these states. This is reflected in multipole mixing ratio values and in internal conversion coefficients. It is anticipated that a better understanding of the nature of m.s. states will, in turn, provide a basis on which we may explain M1 transitions in vibrational nuclei.

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DECAYS OF MASS-SEPARATED ^{181}Au AND ^{181}Pt

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An investigation of decays in the $A = 181$ mass chain was made by producing ^{181}Au ($T_{1/2} = 12\text{s}$) in the reaction $^{175}\text{Lu}(^{16}\text{O}, 10\text{n})^{181}\text{Au}$ with 176-MeV $^{16}\text{O}^{7+}$ beams. The ^{181}Au was mass separated using UNISOR; and the $^{181}\text{Au} \rightarrow ^{181}\text{Pt}$ and $^{181}\text{Pt} \rightarrow ^{181}\text{Ir}$ decay schemes were studied simultaneously using gamma-gamma, gamma-conversion-electron, gamma-X ray, and conversion-electron-X ray coincidence spectroscopy. Some details of the levels observed in ^{181}Ir and ^{181}Pt are given in accompanying contributions to this report. Besides the elucidation of the systematics of low-lying, low-spin levels in the odd-mass iridium and platinum isotopes, these studies are aimed at finding very-converted transitions in the isotopes which would be a signature of shape coexistence.

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SYSTEMATICS OF LOW-LYING STATES IN THE NEUTRON DEFICIENT ODD- MASS PLATINUM ISOTOPES

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The radioactive decays of ^{181}Au ($T_{1/2} = 12\text{s}$), ^{183}Au ($T_{1/2} = 42\text{s}$), and ^{185}Au ($T_{1/2} = 4.2\text{m}$) have been used to populate low-lying low-spin states in $^{181}, ^{183}, ^{185}\text{Pt}$. Nilsson states and associated rotational bands are established in these isotopes as follows:

		^{181}Pt (keV)	^{183}Pt (keV)	^{185}Pt (keV)
1/2-[521]:	1/2-	0	0	103
	3/2-	79	85	181
	5/2-	93	96	201
	7/2-	277	299	424
	9/2-	300	315	452
7/2-[514]:	7/2-	115	35	480
	9/2-	234	150	576
	11/2-	379	289	
5/2-[512]:	5/2-	165	348	510
	7/2-	254	472	615
9/2+[624]:	9/2+	274	196	0

The results are in good agreement with earlier studies of the ^{185}Au decay,⁴ the ^{183}Au decay,⁵ in-beam studies^{6,7} of ^{183}Pt and ^{181}Pt , and an α -decay study^{8,9} of ^{185}Hg .

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SYSTEMATICS OF LOW-LYING STATES IN THE NEUTRON-DEFICIENT ODD-MASS IRIIDIUM ISOTOPES

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The radioactive decays of ^{181}Pt ($T_{1/2} = 51\text{s}$) and $^{183\text{m}}\text{Pt}$ ($T_{1/2} = 43\text{s}$, 6.5m) have been used to populate low-lying, low-spin states in $^{181,183}\text{Ir}$. Ground-state bands in each of these isotopes are very similar to that observed³ in ^{185}Ir and can be interpreted as members of a $1/2^-$ [541] band. Spin-parities and energies (in keV) are: for ^{181}Ir — $5/2^-$ (0), $9/2^-$ (25), $1/2^-$ (112), $3/2^-$ (243), $7/2^-$ (310); for ^{183}Ir — $5/2^-$ (0), $9/2^-$ (16), $1/2^-$ (119), $3/2^-$ (270), $7/2^-$ (329). Excited positive parity states are also observed which can be interpreted as members of rotational bands built on $1/2^+$ [400], $3/2^+$ [402], and $5/2^+$ [402]. Spin-parities and energies (in keV) are: for ^{181}Ir — $3/2^+$, $5/2^+$ (289), $3/2^+$ (299), $1/2^+$, $3/2^+$ (341); for ^{183}Ir — $3/2^+$ (308), $1/2^+$ (320), $5/2^+$ (413), $5/2^+$ (419), $3/2^+$ (472). In addition, the $7/2^-$ [514] isomer in ^{183}Pt is established to strongly populate the $9/2^-$ 514 band in ^{183}Ir in agreement with Ref. 4 and in disagreement with a recent Nuclear Data Sheets evaluation.⁵ The low-lying, positive-parity spin assignments in ^{183}Ir do not agree with a recent in-beam study.⁶

HIGH PRECISION MULTIPOLE MIXING RATIO MEASUREMENTS

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Nuclear orientation offers one of the better ways to obtain multipole mixing ratios. The directional distribution of γ rays from oriented radioactive nuclei depends on the multipolarity of the radiation. When the radiation contains several components, their relative amplitude and phase may often be obtained with high precision. The sensitivity of a measurement depends on the fraction of nuclei which is oriented, and also the spin sequence linked by the γ ray and by the amplitude ratio of the multipole components.

In general, good statistical precision may be obtained since single γ -ray spectra are recorded and, apart from changing the temperature of the sample by $\sim 1^\circ\text{K}$ during a sequence of measurements, all other conditions remain unchanged. When the nuclei that are oriented can be included as a dilute impurity in a well-understood system, operating close to its saturation orientation, then other sources of error may become negligible.

The results of an experiment which satisfied these criteria have recently been published.⁴ High precision measurements of E2/M1 multipole mixing ratios of transitions linking the $K = 2$ and the ground state bands in ^{166}Er reveal that, contrary to the predictions of most nuclear models, sign changes occur. There are also significant changes in the magnitude of the mixing ratios.

These results are difficult to explain on the basis of most geometric models although, by a suitable choice of parameters, it is possible to introduce sign changes which give agreement in some cases.⁵ Thus mixing ratios are sensitive to model tests, but, because of their great sensitivity, they are seldom used and instead intensity ratios and transition probabilities are deduced. We found that the Dynamic Deformation Model, in which the M1 and E2 matrix elements are directly evaluated, provides a satisfactory basis to explain the sign changes and

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also to account for the magnitudes of the measured mixing ratios. The model also indicates that the different types of transitions within the $\Delta K = 2$ group show very different dependences of the matrix elements on the spin change for $\Delta I = 0$ and $\Delta I = \pm 1$ as shown in the Fig. 4.5. We plan to extend the model calculation to higher spins to see if the M1 component in $\Delta I = \pm 1$ transitions might become the dominant one.

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THE LOW ENERGY STRUCTURE OF ^{131}Pm : PREDICTIONS

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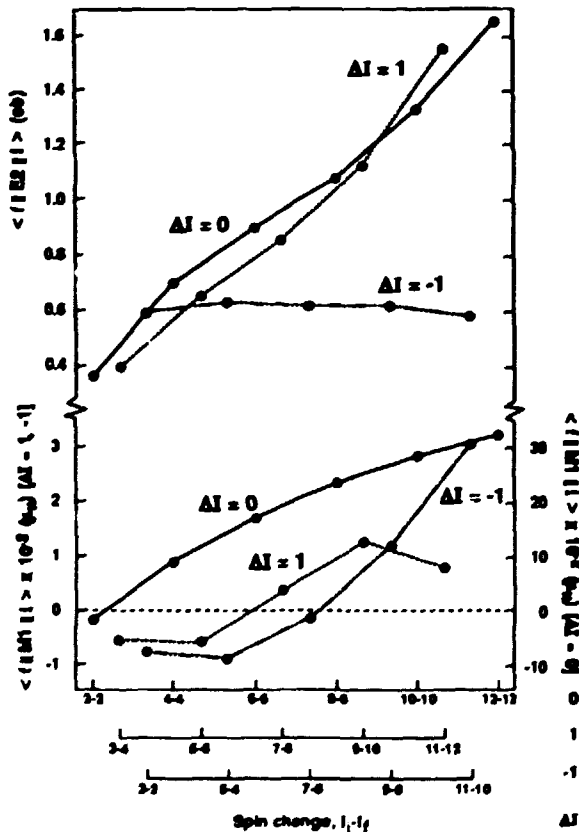


Fig. 4.5. The calculated M1 and E2 matrix elements for transitions linking the γ - and ground-state bands.

Standard calculations have been performed for a number of nuclei in the $A=130$ region within the particle plus triaxial rotor model. These nuclei are one focus of current UNISOR experiments, and are especially interesting because the development of quadrupole shapes has been previously predicted.^{2,3} The calculations presented here build upon these mean field predictions, and attempt to provide details of the low-energy structure expected as the deformation evolves across this mass region. All the model parameters were taken at their standard values, with no adjustment.

The results for ^{131}Pm are summarized in Fig. 4.6. Three rotational bands are evident in the positive parity spectrum, built on the intrinsic Nilsson states $3/2^+$ [411], $5/2^+$ [413], and $9/2^+$ [404]. At the large deformation expected, these bands are quite pure and have distinct M1 properties which can be used to help identify them. In particular, the $B(M1)$'s are expected to be quite weak for the $5/2^+$ [413] band, of moderate strength in the $3/2^+$ [411] band, and strong in the $9/2^+$ [404] band. These features are easily understood in terms of the cooperation/competition between the spin and orbital contributions to the M1 matrix elements, and are reflected in both the $B(M1)/B(E2)$ ratios, as well as the relative gamma intensities. Furthermore, due to the expected purity of these rotational bands, a precise measurement

of the bandhead magnetic moment, along with the $B(M1)/B(E2)$ properties within the band, should allow a determination of both the intrinsic g factor (g_K) and the intrinsic quadrupole moment, and hence the deformation.

Also, the position of the $9/2^+$ [404] band depends sensitively on the deformation and is not expected within an MeV of the ground state unless $\beta \geq 0.27$. Thus, observation of the $9/2^+$ [404] band alone is a clear indication of large prolate deformation.

In contrast, the predicted energy level pattern of the negative parity states is rather stable with deformation, because the Fermi level is in the middle of the $h_{11/2}$ sub-shell. Also, the rotational band structure is quite distorted, so that it is not possible to observe both crossover and cascade transitions. For these states, a $B(E2)$ (lifetime) measurement will be necessary to get a clear indication of the deformation. However, such measurements often are not feasible.

¹³¹Pm₆₁ Calculations: W-S potential $\beta = 0.305$ $\gamma = 0$ $\beta_4 = +0.012$

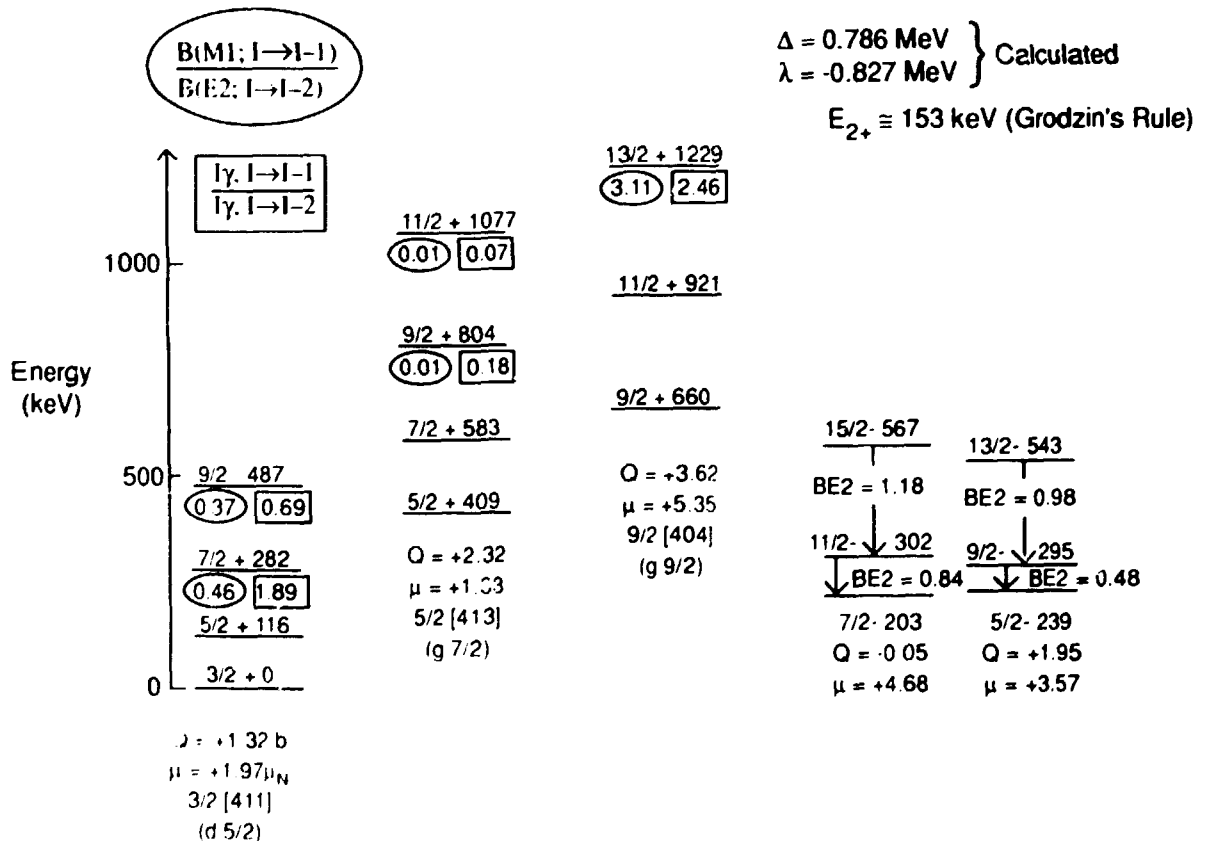


Fig. 4.6 Predicted level structure for ¹³¹Pm.

Finally, the heavier Pm isotopes should be less deformed, and consequently the rotational bands less pure, and many of the features described above less distinct. Thus, the characteristic features predicted for ^{131}Pm can be used to signal the onset of strong deformation.

1. Tennessee Technological University, Cookeville.
2. G. A. Leander and P. Moller, *Phys. Lett.* **110B**, 17 (1982).
3. B. D. Kern, et al., *Phys. Rev. C* **36**, 1514 (1987).

STUDY OF THE DECAY OF $^{114,116}\text{I}$ TO LEVELS OF $^{114,116}\text{Te}$

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W. B. Walters¹ P. F. Mantica, Jr.³
J. Rikowska² T. S. Lam⁴
J. Kormicki⁵

We have investigated the decay of the odd-odd nuclides, $^{114,116}\text{I}$ to levels in the even-even Te nuclides, $^{114,116}\text{Te}$. The purpose of these studies has been both to study the structure of these odd-odd nuclides by measuring their magnetic moments using the Nuclear Orientation Facility at the UNISOR beam line and to study the structure of the even-even Te nuclides.

The low-energy levels of ^{116}Te populated in the decay of ^{116}I are shown in Fig. 4.7. We are in agreement with previous studies about the levels up to 1500 keV and also observe additional levels above that energy but believe the spins to be lower than previously proposed. No E0 branch was observed for the 1060 level.

Subsequently, a nuclear orientation experiment was conducted for this nuclide. An upper limit of 2% anisotropy was established at 16 mK for the Fe foil that we used. During the same experiment, $8 \pm 2\%$ anisotropy was observed for the granddaughter ^{116}Sb . When these data are combined with previous data for ^{116}Sb , about 40% of the nuclides appear to be in good sites in the Fe lattice.

Assuming the same value for I leads to an upper limit of 0.5 nuclear magnetons for the moment of $1^+ ^{116}\text{I}$. This value is much smaller than expected.

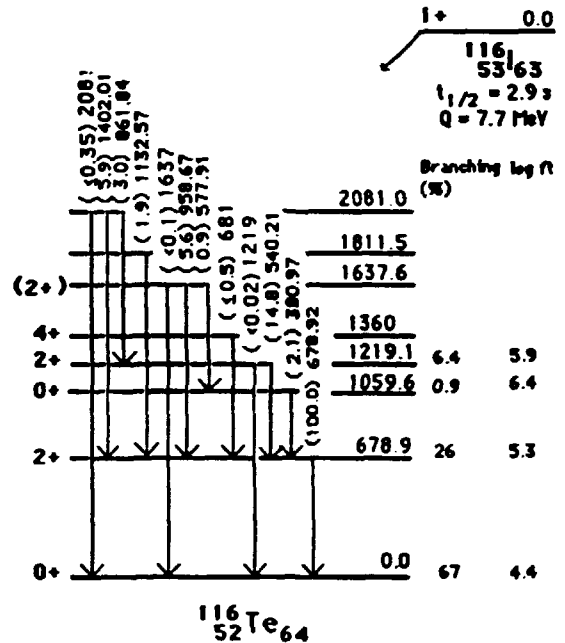


Fig. 4.7. Proposed level scheme for ^{116}Te .

New data have also been obtained for ^{114}I decay and is shown in Fig. 4.8. The much larger population of the 4^+ level in the decay of ^{114}I as contrasted with ^{116}I can be used to suggest that the ground state spin of ^{114}I is either 2^+ or 3^+ . The levels that we propose in the daughter ^{114}Te are in disagreement with previous work. We did not observe the gamma rays at 633 and 1342 keV previously suggested for this nuclide, but did observe the transitions shown and did observe coincidence data to support these suggested levels.

Calculations using the IBFFM model for odd-odd nuclides are planned to determine which configurations for ^{116}I would be consistent with the small moment value that our data suggest.

RADIOACTIVE HEAVY ION BEAMS

W. D. Hamilton¹

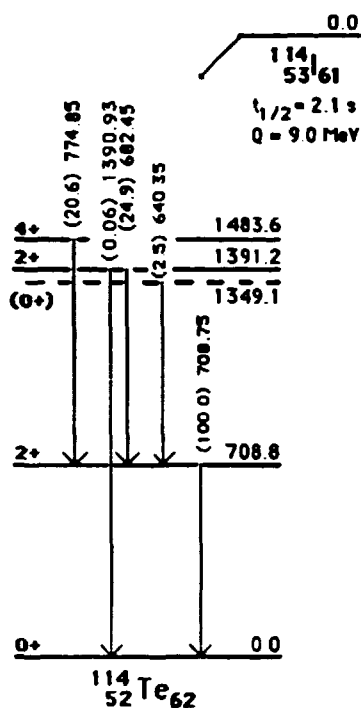


Fig. 4.8. Proposed level scheme for ^{114}Te .

A source of radioactive ions may be created by extracting the products from a neutron-induced fission reaction. The source may be located either within the moderator or on an external beam, close to the reactor. The former would have the considerable advantage that no additional biological shielding would be required while positioning the ion source on an external beam would allow easier access. Copious amounts of ions may be produced since heavy element targets such as ^{235}U , ^{244}Pu , and ^{251}Cf are essentially black to neutrons for a modest target thickness. Indeed, target heating may be a limiting feature if the flux that is planned for the Oak Ridge Advanced Neutron Source, 8.5×10^{15} neutrons $\text{cm}^{-2}\text{s}^{-1}$, were to become available.

A reactor based source offers many advantages compared to dedicated accelerator facilities such as those recently discussed.^{2,3} It is only a small part of the total research effort that can be supported by a high-flux reactor; at the ILL in Grenoble there may be as many as 100 experiments running simultaneously. It would thus appear to be a very cost-effective approach. A reactor is also a very stable operating system with the flux remaining constant throughout the long periods of many weeks between fuel changes. The range of isotopes that may be made available depends on the fissionable target and on the neutron spectrum. Epithermal neutrons will lead to more symmetric fission while heavier targets will also tend to reduce the valley depth between peak yields and at the same time increase the range to a greater mass. We might expect useful yields within the mass range A~80 to ~160 and neutron excesses of up to 8 beyond the most stable isotope. These neutron rich isotopes have a half-life of $T_{1/2} > 1$ s and this is sufficiently long for many elements so that hold-up times in the ion source will not greatly affect yields.

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2. JIHIR, Oak Ridge, TN. Present address: Oxford University, United Kingdom.
3. UNISOR, Oak Ridge Associated Universities, Oak Ridge, TN.
4. Louisiana State University, Baton Rouge.
5. UNISOR, Oak Ridge Associated Universities, Oak Ridge, TN and Vanderbilt University, Nashville, TN.

From the point of view of reaction spectroscopy, neutron rich isotopes offer the chance of creating excited high-spin nuclei close to the stability line where it may be expected that the highest possible spin states will be formed. These isotopes will also enable heavy elements to be formed since the enhanced N/Z ratio will be a considerable advantage and reaction products will lie closer to the stability line.

1. JIHIR, Oak Ridge, TN and Vanderbilt University, Nashville, TN. Present address: Mississippi State University, Mississippi State.

2. *Radioactive Nuclear Beams*, ed. W. D. Meyers, J. M. Nitschkei, and E. B. Norman, World Scientific (1990).

3. *Proceedings of the Workshop on the Science of Intense Radioactive Beams, Los Alamos National Laboratory*, ed. J. B. McClelland and D. J. Vieira, LA-11964-C (1990).

5. EXPERIMENTAL ATOMIC PHYSICS

ACCELERATOR-BASED ATOMIC PHYSICS

MEASUREMENTS OF PAIR PRODUCTION IN RELATIVISTIC HEAVY PARTICLE COLLISIONS

S. Datz, P. F. Dittner, H. F. Krause, C. R. Vane, A. Belkacem,¹ B. Feinberg,¹ H. Gould,¹ R. Schuch,² H. Knudsen,³ and P. Hvelplund³

Using the 200-GeV/nucleon sulfur beam at the CERN SPS accelerator, we have made initial measurements of the differential cross sections for electron-positron pair production in Coulomb collisions of fast ions on heavy targets. Electrons and positrons emitted from thin palladium and gold targets under sulfur ion impact were magnetically separated, analyzed and counted in two discrete arrays of silicon surface barrier detectors. A schematic of the experimental apparatus is shown in Fig. 5.1.

Coincidences between positron, electron, and undeflected projectile ions were used to distinguish real pairs from background signals and from electronic noise. Signals identifying the coincident projectiles as sulfur ions were provided by the WA80 collaboration experiment which was simultaneously operating downstream of the experiments reported here. Yields for knock-on electrons (deltas), as measured on both detector arrays, were determined for thin aluminum targets in which pair production is insignificant and for thin gold targets. A direct comparison of these measured yields with results of a computer simulation for knock-ons has been used to establish a set of absolute detection efficiencies for use in converting the pair yields to cross sections. Calculations were based on binary collisions of 200-GeV/nucleon sulfur ions on free electrons. Multiple Coulomb scattering of low energy electrons in the target was simulated in the calculations by appropriately smearing the initial angular distributions. A ray tracing routine which incorporated measured field components for the analyzing magnet was used to track individual electrons to the detector plane where counting bins accumulated signals for each detector. Both calculated and measured counts from several individual detectors

corresponding to a given electron momentum range were then summed into nine bins. Figure 5.2 displays calculated and measured momentum distributions for knock-on electrons from a 1.9 mg/cm² aluminum target.

ORNL-DWG 90-16973

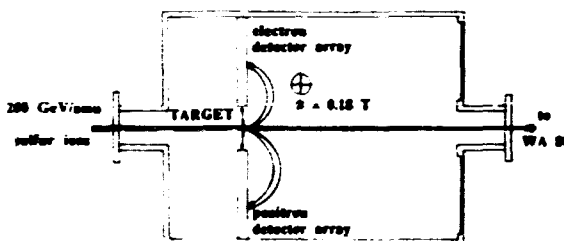


Fig. 5.1. Schematic of experimental apparatus showing electron and positron trajectories in the uniform magnetic analyzing field. The two detector arrays were composed of 41 discrete silicon surface barrier detectors arranged to cover approximately 50% of the available areas on either side of the target. At a magnetic field setting of 0.18 Tesla, electrons and positrons having 0.9 to 7.0 MeV/c momenta fall on the detectors.

Our preliminary analysis of the data gives a partial cross section for creation of electron-positron pairs of 74 barns. This value is for positrons having momenta between 0.9 and 7.0 MeV/c and for emission within $\pm 20^\circ$ of the forward direction. The corresponding theoretical result of Botcher and Strayer⁴ is 51 barns. Figure 5.3 shows the measured momentum distribution for positrons from gold targets compared with the corresponding theoretical predictions.^{4,5} Figure 5.4 gives measured positron yields per incident undeflected sulfur ion for various target thicknesses. Included in Fig. 5.4 is one data point taken using a 9.6 mg/cm² palladium ($Z=46$) target. The palladium positron yield has been plotted

there for an effective gold target thickness scaled according to the square of the ratios of the atomic numbers $(46/79)^2$, as predicted by theory.

ORNL-DWG 90-16974

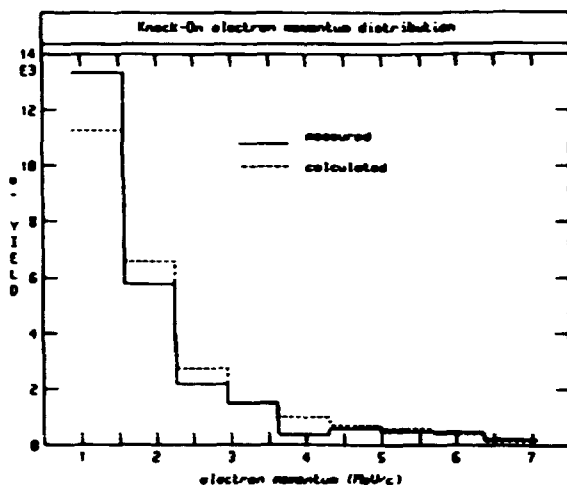


Fig. 5.2. Calculated and measured momentum distributions for knock-on electrons from a 1.9 mg/cm² aluminum target as detected in the positron detector array.

ORNL-DWG 90-16979

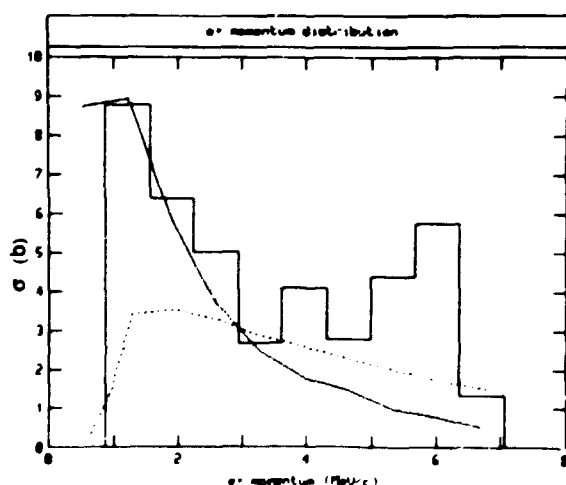


Fig. 5.3. Momentum distribution for positrons from collisions of 200-GeV/nucleon sulfur ions on thin solid gold targets. Measured values are displayed as points. Calculations are displayed as lines: Ref. 4 —, Ref. 5 - - - -.

ORNL-DWG 90-16975

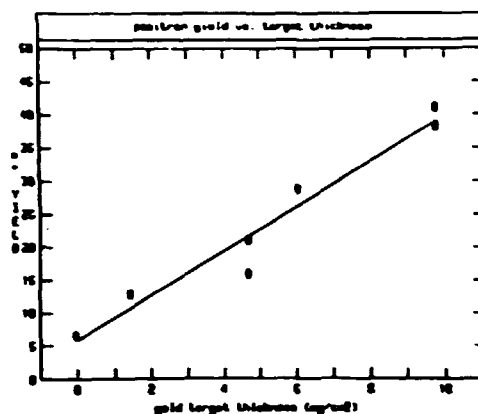


Fig. 5.4. Measured yields for positrons in coincidence with unscattered sulfur ions plotted as a function of gold target thickness. Yields represent integration of cross section over full detected momentum and angular ranges of 0.9-7.0 MeV/c and 0-20 degrees, respectively. Single (*) data point is for a 9.6 mg/cm² palladium target, with the target thickness scaled according to target atomic number squared $(46/79)^2$, as predicted by all theories.

1. Lawrence Berkeley Laboratory, Berkeley, California.
2. Manne Siegbahn Institute of Physics, Stockholm, Sweden.
3. Aarhus University, Aarhus, Denmark.
4. C. Botcher and M. R. Strayer, *Phys. Rev. D* 39, 1330 (1989); and private communications.
5. P. B. Eby, *Phys. Rev. A* 39, 2374 (1989).

DIELECTRONIC EXCITATION OF IONS IN CRYSTAL CHANNELS

S. Datz, C. R. Vane, P. F. Dittner, H. F. Krause, U. Bechthold,¹ J. Gomez del Campo, R. Watton,² P. Zeijlmans van Emmichoven,³ and N. L. Jones

For an ion traversing a crystal channel with velocity substantially greater than the Fermi velocity of the electrons in the channel, the system may be viewed from the ion's perspective as a high flux of bombarding electrons with velocities distributed narrowly about that of the ion. Dielectronic excitation can occur when one- or multi-electron ions

travel through such a medium at appropriate velocities. Doubly excited states are formed which, in vacuum, would stabilize either by Auger emission or by radiative relaxation. In the relatively dense electron gas medium provided by a crystal channel, secondary electron-ion collisions can lead to further excitation and/or ionization prior to either Auger or radiative decay. In previous measurements⁴ we found close agreement between experiment and theory for absolute X-ray yields and final charge state fractions calculated using scaled radiative transfer and excitation (RTE) cross sections⁵ for ions in hydrogen gas, tabulated radiative and Auger rates,⁶ and ionization and excitation cross sections estimated from simple parametric formulae of Lotz and Seaton,⁷⁻⁹ respectively. To quantitatively test the effects of secondary collisions, we have varied target thickness and measured K X-ray emission yields and exit charge state fractions over the KLL dielectronic resonances for H-like Ti and He-like Ti ions channeled through the $\langle 110 \rangle$ axis of silicon single crystals. X rays were measured in coincidence with titanium ions having undergone electron capture. Absolute yields of X rays have been converted to cross sections per target electron. The results for the H-like and He-like Ti ions are 1.16 and $0.70 \times 10^{-21} \text{ cm}^2$, respectively. RTE cross sections for H-like and He-like Ti ions have not been measured previously, so a direct comparison with our results is not possible; but RTE cross sections for H-like and He-like Ca ions have been measured. Since the underlying dielectronic recombination cross sections vary only slowly with Z in this region of Z , we can then compare our results with the measurements of Tanis et al.⁵ for Ca ions. In order to compare our cross sections with Ref. 5 (see Table 5.1), we divided their numbers by two to convert from cross section per hydrogen molecule to per electron. Further, since the target electron momentum distributions (EMD) are not the same in the two experiments (our EMD determined by the Fermi width of the crystal channel, their EMD by the Compton profile of H_2), we need to compensate by multiplying our result by 1.12. The agreement between our measured cross sections and the previous RTE measurements is very good (see Table 5.1).

Table 5.1. Comparison of Resonant Transfer and Excitation Cross Sections for H-like and He-like Ions

Cross Section/Electron (in units of 10^{-21} cm^2)		
	Ca(a)	Ti(b)
He-like	1.3	1.3
H-like	0.95	0.78

(a) Ref. 5.

(b) This work.

1. Graduate student from the University of Frankfurt, Germany.

2. Department of Physics, Texas A and M University, College Station.

3. Guest assignee from Rijksuniversiteit Utrecht, the Netherlands.

4. S. Datz et al., *Phys. Rev. Lett.* **63**, 742 (1989).

5. J. A. Tanis et al., *Phys. Rev. A* **34**, 2543 (1986).

6. J. F. Seely, *At. Data Nucl. Data Tables* **26**, 137 (1981).

7. W. Lotz, *Z. Phys.* **206**, 206 (1968).

8. R. A. Phaneuf, p. 139, Eq. 3.7, in *Atomic Processes in Electron-Ion and Ion-Atom Collisions*, ed. F. Brouillard (Plenum, New York, 1986).

9. M. J. Seaton, in *Atomic and Molecular Processes*, edited by D. R. Bates (Academic, New York, 1962), p. 374.

RESONANT COHERENT EXCITATION OF HYDROGENIC Mg IONS IN A GOLD CRYSTAL

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An ion passing through a thin single crystal along an axis of symmetry experiences an oscillating potential with a fundamental frequency given by

$f = v/d$, where v is the ion speed and d is the atomic core spacing along the ion's direction. When this fundamental frequency or a higher harmonic matches an electronic transition energy for the ion (in the presence of the crystal and wake fields) resonant coherent excitation (RCE) can occur. In previous works, we have studied this process extensively for ions lighter than neon.⁶ For these light ions, the probability for secondary collisional stripping of excited electrons in the remaining path length of the crystal is high, resulting in significant variation of the surviving charge state fractions as the primary signature for RCE. For heavier ions, survival of the excited states to the crystal exit surface becomes relatively more probable and emission of X rays is then a more important relaxation mode. We have recently begun an investigation of radiative relaxation of the RCE-produced $n = 2$ states for hydrogenic magnesium ions axially channeled in gold. One-electron magnesium ions from the HHIRF tandem were collimated and axially channeled through a 2000-Å-thick Au <100> crystal. Projectile K X rays emitted at 45 degrees were detected using a high resolution Si(Li) detector. Surviving charge-state fractions were measured with a magnetic charge-state analyzer and position-sensitive ion detector. Some results are displayed in Figs. 5.5 and 5.6. The fourth harmonic resonance of $n = 1$ to 2 transitions for hydrogenic Mg in vacuum should appear at 163 MeV. Electric fields in the crystal shift the peaks to lower energies. The upper of the two peaks corresponds to excitation into a $2p_z$ state, while the lower corresponds to a $2p_x$ or a $2p_y$ state. Comparison of the charge-state and X-ray yield curves shows that the probability of escape from the crystal without ionization (X-ray data) is greater for ions in the $2p_z$ state than for those in the $2p_{x,y}$ states. The data shown are preliminary, and offered only as proof of principle for experiments which will allow us to measure electron bombardment ionization cross sections for short lived excited states with specific polarization.

ORNL-DWG. 90M-14665

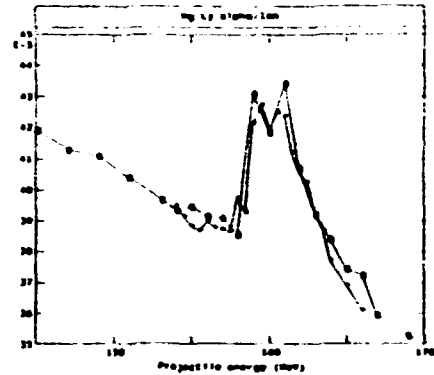


Fig. 5.5. Resonant coherent excitation of Mg^{11+} (4th harmonic) in <100> Au observed as Mg $Ly\alpha$ emission; yield of X rays as a function of Mg^{11+} energy.

ORNL-DWG 90-14666

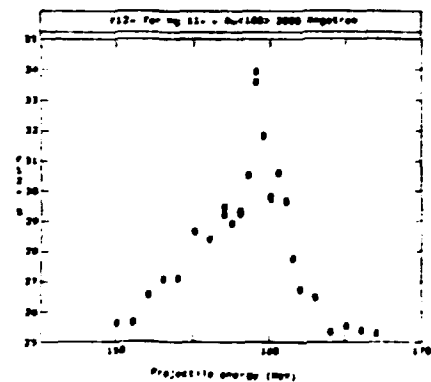


Fig. 5.6. Resonant coherent excitation of Mg^{11+} (4th harmonic) in <100> Au observed by increase in ionization; charge fraction of Mg^{12+} as a function of Mg^{11+} energy.

1. Graduate student from the University of Frankfurt, Germany.
2. Guest assignee from Rijksuniversiteit, Utrecht, the Netherlands.
3. University of Osaka, Osaka, Japan.
4. University of Tokyo, Tokyo, Japan.
5. University of Kyoto, Kyoto, Japan.
6. S. Datz and C. D. Moak, "Heavy Ion Channeling," in *Treatise on Heavy-Ion Science*, ed. D. A. Bromley, Vol. 6, Astrophysics, Chemistry, and Condensed Matter, Ch. 5 (1985) pp. 169-240.

RADIATIVE ELECTRON CAPTURE BY BARE AND ONE-ELECTRON IONS

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Electron transfer to fast heavy ions traversing single crystal channels, where collisions are mainly restricted to those with only weakly bound electrons, proceeds primarily by the process of radiative electron capture (REC). In precise measurements of REC X rays emitted by bare and one-electron sulfur and titanium ions axially channeled through thin silicon crystals, it was found that the energies of REC X rays observed at 45 degrees with respect to the beam axis fall consistently below the predicted values by 70-100 eV, as is displayed in Fig. 5.7. We have extended and improved these experiments incorporating: X-ray/channel-ion coincidence requirements, measurements at two observation angles (45 and 90 degrees), and measurements at higher and lower beam energies for bare sulfur and titanium ions channeled in silicon along both the $\langle 110 \rangle$ and $\langle 100 \rangle$ axes. Meanwhile, improvements have also been made in theoretical treatments^{6,7} to include effects of the ion's wake as well as small energy shifts in the REC peak due to capture of more tightly bound, inner-shell electrons whose wave functions extend into the crystal channels. For sulfur ions in silicon, for which the most precise calculations have been made, the combination of all these shifting effects appears to account for all but about 30-40 eV of the observed energy deficits. Our estimated total uncertainty in these measurements is 20 eV. However, the same theoretical treatments predict REC peak widths far exceeding our measured values. For example, Ref. 6 yields 620 eV for the full width at half maximum for 160-MeV sulfur channeled in silicon $\langle 110 \rangle$, while we measure 480 ± 20 eV.

We have also measured the absolute REC yields and peak profile widths, as well as the energy loss of the fully stripped ions in passing through the crystals. The REC peak profiles are all well fit by assuming that the target electron velocity distributions experienced are those described by a free-electron gas with a Fermi energy in silicon of 10.6 eV. Using the three independent measurements of (1) REC yield per incident ion, (2) REC profile width, and (3) channeled

ion energy loss, three quasi-independent values of the electron target density have been obtained as indicated in Table 5.2 for Ti^{22+} ions channeled in an 0.8- μm -thick Si $\langle 100 \rangle$. These values were calculated assuming a free-electron gas model for the target and using the appropriate relations between electron density and Fermi velocity. The three densities obtained agree to within 12%, thus supporting our hypothesis that the primary collisional effects for channeled ions may be calculated assuming interactions with a free-electron gas.

ORNL-DWG 90-16972

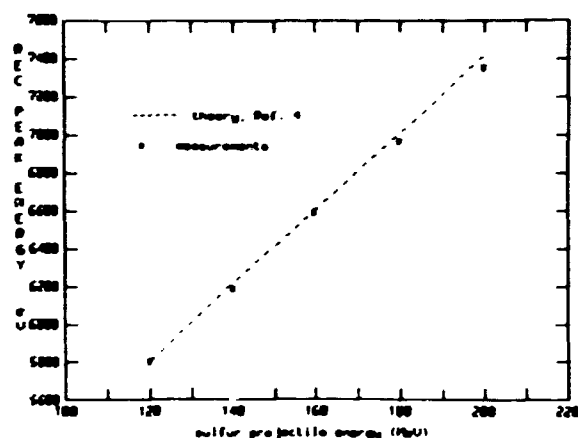


Fig. 5.7. Calculated and measured REC X-ray peak positions for S^{16+} ions channeled through a silicon $\langle 110 \rangle$ crystal 4200 Å thick.

Table 5.2. Effective Electron Densities for a Si $\langle 100 \rangle$ Target.

Measurement Method	Result ($\times 10^{23}/\text{cm}^3$)
1. REC Yield/ion	1.6
2. REC Profile Width	1.6
3. Energy Loss	1.3

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2. Analytical Chemistry Division, ORNL.
3. Department of Physics, University of Missouri, Rolla, MO.
4. Graduate student from the University of Frankfurt, Germany.
5. Department of Physics, Texas A and M University, College Station.
6. J. M. Pitarke, R. H. Ritchie, and P. M. Echenique, submitted to *Physical Review A* (1990).
7. J. Burgdörfer, *Proceedings of Fourth Workshop on High Energy Atomic Collisions*, September 17-21, 1990, Debrecen, Hungary.

HIGH-RESOLUTION X-RAY SATELLITE EMISSIONS FOR SULFUR IMPLANTED IN QUARTZ

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N. L. Jones, J. Young,¹ and R. Zuhr³

A series of quartz glass targets have been implanted to a depth of 90 nm with approximately equal doses of 70-keV sulfur and 35-keV oxygen ions ranging from 0.5 to $10 \times 10^{16}/\text{cm}^2$ at the ORNL Surface Modification and Characterization Facility. Using high-resolution measurements, the relative fluorescence yields of sulfur K-X-ray satellite lines produced by impact of 24-MeV silicon ions obtained from the ORNL EN-Tandem accelerator have been determined. These data were then compared to similar data from a series of quartz targets implanted with sulfur alone. The data exhibit lower yields for the co-implanted oxygen samples but have similar dose-dependent curves. These results are consistent with an increase in the valence electron density of the local sulfur environment by the co-implanted oxygen, suggesting that, with appropriate choice of ion probe, measurements of heavy ion excited X rays may be capable of detecting a wide range of impurity ions including even oxygen in oxide substrates.

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2. Department of Physics, University of the South, Sewanee, TN.
3. Solid State Division, ORNL.

EN TANDEM OPERATIONS

P. F. Dittner and N. L. Jones

During the past year, the EN Tandem operated for ~2000 hours in support of the Accelerator-Based Atomic Physics Program. Operation was between 0.45 and 5.4 million volts on the terminal, accelerating beams of ions from hydrogen through iodine. Intense ($>10 \mu\text{A}$) beams of chlorine, bromine, silver, selenium, and iodine were developed and accelerated from our Alton-Aarhus negative ion source. A new method of applying charge to the charging belt was tested successfully, using shim stock instead of wire screens. This method has reduced the production of belt dust drastically, resulting in more stable operation at high voltages. Diagnostics of the terminal voltage ripple caused by belt irregularities is in progress using an audio frequency analyzer. The facility was utilized by ORNL Physics Division staff, by researchers from other ORNL divisions, and by outside users from the University of North Carolina, U.S. Naval Academy, Kansas State University, University of Connecticut, University of the South, University of Tennessee, Texas A&M University, Francis Marion College, and foreign institutes such as Manne Siegbahn Institute, (Stockholm, Sweden) and Kyoto University (Japan).

STUDY OF LANDAU RESONANCES WELL ABOVE THRESHOLD IN A LASER PHOTODETACHMENT

H. F. Krause

The novel high-resolution crossed-beams photodetachment apparatus demonstrated last year¹ was used in a systematic study of Landau resonances associated with the most intense $\text{O}^-(^2P_{3/2}) \rightarrow \text{O}(^3P_{j=2,1})$ fine-structure transitions. In this study, the effects of Stark splitting and Doppler broadening were essentially eliminated. The equivalent electron energy resolution of the photoejected electrons, E/dE , exceeded 1×10^6 (Ref. 2).

Photodetachment cross sections with and without an applied magnetic field, shown in Fig. 5.8, were measured by counting neutral O atoms. Periodic but weak variations in the cross section (typically below

15%) occurred at the surprisingly low magnetic field of 0.126 Torr and for photoelectrons ejected at 0.045 eV as shown in Fig. 5.8 (a). No structure within statistics was observed with the field turned off as shown in Fig. 5.8 (b). Under these conditions, the Landau resonances have a very large principal quantum number ($n \approx 3000$). Theoretically predicted Zeeman line strengths for $O^-(^2P_{3/2})$ leading to $O(^3P_2)$ and $O(^3P_1)$ are shown at measured patterns A and B, respectively. Symmetry of observed line strengths suggested the phasing of A and B shown in Fig. 5.8 (a). Comparing the $O(^3P_2)$ theoretical line strengths to the measured spectrum at position A, we see that the strong predicted central line is weak and the predicted weak lines are strong. The comparison of $O(^3P_1)$ line strengths at position B is more favorable except for a stronger central line that should not appear. The Zeeman line intensities observed do not agree with those predicted by theory. The suggested breakdown of the theoretical treatment that predicts line strengths³ will be further tested in future experiments performed at threshold.

1. H. F. Krause, *Phys. Div. Prog. Report for Period Ending Sept. 30, 1989*, ORNL-6578, p. 161.
2. H. F. Krause, *Phys. Rev. Lett.* **64**, 1725 (1990)
3. W. A. M. Blumbert, W. M. Itano, and D. J. Larson, *Phys. Rev. A* **19**, 139 (1979).

PHOTODETACHMENT OF B^- AND Li^-

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and G. D. Alton

The photodetachment measurements on B^- and Li^- ions represent a continuation of a program to determine cross sections for single-photon, single-electron photodetachment of atomic negative ions. In the present experiments, a crossed laser-negative ion beams apparatus is being used to make energy- and angle-resolved spectroscopy measurements of photoelectron yields and angular distributions. The experiments exploit, in a novel manner, kinematic effects associated with detachment of electrons from fast beam sources.

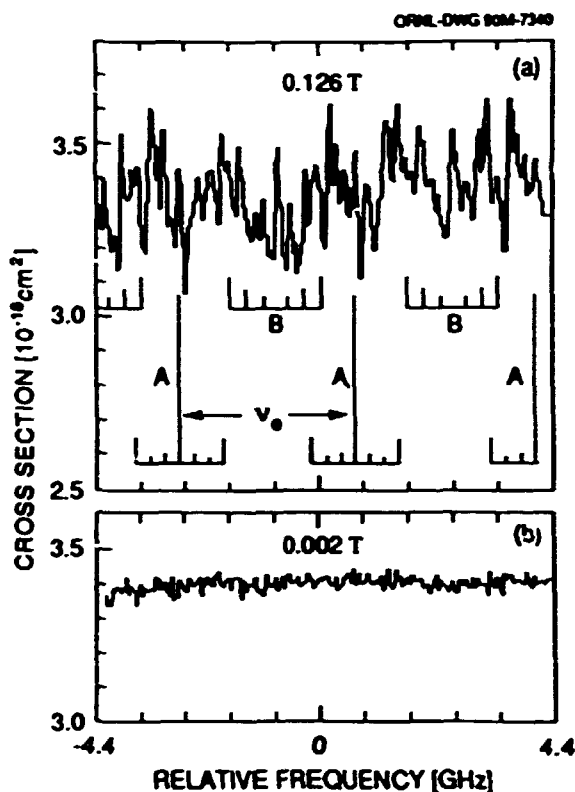


Fig. 5.8. (a) Photodetachment cross section for O^- in a magnetic field of 0.126 Torr in the vicinity of 12147.06 cm^{-1} . The incident light is linearly polarized in the direction of the field (i.e., $\Delta M=0$ transitions). Weak repetitive structure occurs at the electron cyclotron frequency ($\nu_c = 3.53 \text{ GHz}$). Theoretically predicted Zeeman line strengths for $O^-(^2P_{3/2})$ leading to $O(^3P_2)$ and $O(^3P_1)$ are shown at positions A and B, respectively. (b) Photodetachment cross section measured under identical conditions but with the magnetic field turned off. This "field free" cross section is approximately equal to the cross section of (a) averaged over the Landau period.

There have been no previous investigations, experimental or theoretical, of the cross sections for photodetaching an electron from the stable B^- ion. The B^- ion is formed in the $(1s^2 2s^2 2p^2)^3P$ state when an electron is attached to the $(1s^2 2s^2 2p)^2P$ ground state of the B atom. Single-photon, single-electron photodetachment proceeds via the process: $h\nu + B^-(^3P) \rightarrow B(^2P) + e^-(k, s, d)$. The cross sections for this process are determined by measuring the yields and angular distributions of photoelectrons ejected from

the interaction region between crossed laser and B^- ion beams. The asymmetry parameter completely characterizes the shape of the photoelectron emission pattern. Over the spectral range from -1.75 to 2.10 eV, the asymmetry parameter stays essentially constant at 0.18 ± 0.04 . Cross sections for photodetaching B^- have been measured relative to those for photodetaching He^- via the $He(2^3P)$ channel. The He^- cross sections, in turn, were measured relative to those for photodetaching D^- . Thus the B^- cross sections have been indirectly normalized to the well-known theoretical values for the H^- photodetachment cross sections. We are now starting measurements of the B^- cross sections made relative to those for photodetaching Li^- . In the laboratory frame, the electron peaks from photodetaching both He^- and B^- each have an energy of ~ 7.5 eV. This energy alignment was attained by kinematically shifting the electron peaks using an appropriate choice of the ion beams energies. Under such conditions, the efficiencies for collection and detection of photoelectrons at the same energy from the two beams are equal and thus cancel in the ratio measurement. Thus far we have measured two B^- photodetachment cross sections. At a wavelength of 696.2 nm (1.78 eV), the cross section is 16.5 ± 2.1 Mb. At a wavelength of 636.7 nm (1.94 eV), the cross section is 14.3 ± 2.2 Mb. Measurements at other visible wavelengths are in progress.

The Li^- ion has been described as an effective three-body system consisting of two highly correlated electrons orbiting a screened positive charge. In this approximation, one assumes that the two core electrons that screen the nucleus are otherwise frozen. There have been several attempts to calculate the cross sections for photodetaching the stable Li^- ion. The accuracy of the best of these calculations is estimated to be $\sim 10\%$. In contrast, there appears to be only two experimental studies of Li^- photodetachment cross section to date. The best data, taken over a limited energy range, has an estimated accuracy of $\sim 15\%$. We have recently begun a series of measurements aimed at determining cross sections for photodetaching an electron from Li^- at several discrete wavelengths across the visible spectrum. In these measurements, as in our previous photodetachment cross section measurements, we attempt to measure the ratio of the cross section for photodetaching Li^- to that for

photodetaching a reference ion, D^- in this case. The photoelectron emission exhibited the expected $\cos^2\theta$ form ($\beta = 2.00$), with an estimated accuracy of $\sim 2\%$. The preliminary result for the cross section ratio, at a photon energy of 1.87 eV, is $\sigma(Li^-)/\sigma(D^-) = 1.98 \pm 0.15$. A scale for this relative measurement can be established by the use of a theoretical value for the photodetachment cross section for H^- . We arbitrarily choose the value of $\sigma(H^-) = 37.1$ Mb (estimated accuracy of $\sim 3\%$) calculated by Stewart.⁴ The photodetachment cross section of Li^- then becomes $\sigma(Li^-) = 73.5 \pm 6.0$ Mb. The value compares favorably with theory.

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4. A. L. Stewart, *J. Phys. B* 11, 3851 (1978).

ELECTRON ENERGY DISTRIBUTIONS DIFFERENTIAL IN RECOIL- AND PROJECTILE-ION CHARGE STATES IN FAST ION-ATOM COLLISIONS

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Target electrons emitted in fast ($\sim$ MeV/nucleon) ion-atom collisions reflect the ionization processes involved. An additional differentiation in recoil charge state proves to be a stringent test of existing theoretical models. We have measured energy distributions of electrons from Ne, Ar, and Kr targets following bombardment by 7.5 and 10 MeV C^{6+} ions. Recoil ions and target electrons were extracted simultaneously and a retardation technique was used to analyze the energy of the electrons. The mean electron energy was found to increase with recoil charge state for direct ionization but was independent of the recoil charge state for simultaneous capture to the projectile. For Ar and Kr targets, a strong enhancement in the electron distribution at $100 - 120$ eV was found, which cannot be explained by Auger transitions. The measured enhancement was most pronounced for direct ionizing collisions and could not

be found in collisions with Ne targets. Theoretical calculations of multiple ionization using binomially distributed, single-electron transitions explains the measured recoil ion distribution, but fails to describe the observed electron enhancement at 100 eV. Calculations including target polarization, such as *n*-particle, classical-trajectory Monte Carlo, were more appropriate in describing the observed structures. The measured projectile energy loss associated with the observed electron energy distributions exceeds, depending on the target, the ionization potential by up to a factor of 10. Both the *n*-particle, classical-trajectory Monte Carlo calculations, as well as the calculations based on binomially distributed single ionization probabilities cannot account for the large projectile-energy loss. With the measured anisotropy in the angular distributions of the ionized target electrons, strong deviations from the binary collision are to be expected.

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ANGULAR DISTRIBUTIONS OF ONE- AND TWO-ELECTRON CAPTURE IN VERY SLOW Ar^{6+} - Ar COLLISIONS

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The need for experimental and theoretical information on charge exchange mechanisms in laboratory and astrophysical plasmas is one of the many reasons for the growing attention in the field of electron capture by slow multiply charged projectile ions.⁷ At low collision velocities (when the relative velocity between the projectile and the target is much smaller than the orbital velocity of the active electron) the process of state-selective electron capture can be described within a quasimolecular picture. In many of these cases, electron transfer takes place near well-localized avoided crossings between adiabatic potential energy curves of the same spin and symmetry. Total

and differential cross sections can be calculated using a multichannel Landau-Zener formalism. This method has been applied with success to explain recent results for very slow Ar^{4+} - Ar collisions.^{8,9} This report covers experimental results for Ar^{6+} - Ar collisions in the energy range of 32 to 800 eV.

The experimental setup has been described in a previous report.⁹ Here we only give a brief summary and note significant changes. Argon recoil ions are produced by a fast ion beam from the ORNL EN-12 Tandem Van de Graaff accelerator. The ions are extracted by a small electric field and then accelerated to the potential of a Wien-filter for mass-to-charge separation. After retardation and collimation, the very slow ion beam crosses an effusive gas-jet target at right angles. After the interaction, the charge states, energies, and scattering angles of the projectiles are analyzed by a 64° cylindrical electrostatic analyzer and a multichannel plate with a two-dimensional position-sensitive anode. Since the analyzer focusses only in one dimension, information on the energy gain values is obtained from the position recorded along the direction of energy dispersion, while scattering angles are derived from the vertical position on the detector. The relative energy resolution is about 1.6%. The angular divergence of the very slow ion beam was measured to be about $\pm 0.5^\circ$ and the acceptance angle is limited to $\pm 9^\circ$ by the diameter of the position-sensitive detector.

The experimental energy-gain spectra show that single-electron capture mainly populates the 5s and 5p levels, in accordance with observations at higher collision energies.¹⁰ The energy-gain spectrum for single-electron capture in Fig. 5.9 is observed at larger scattering angles and shows additional peaks around $Q = 26$ eV associated with transfer ionization. Energy-gain spectra for true double-electron capture show two structures corresponding to inelasticities of $Q = 26$ eV and 42 eV. These *Q*-values indicate total binding energies for two electrons captured to the Ar^{6+} projectile of 69 eV and 85 eV, respectively. The binding energy of the Ar^{5+} ground state is 91 eV with respect to Ar^{6+} . Binding energies for relevant doubly-excited states are not readily available in tables, but some information on their structure can be gained by using an extended Rydberg formula given by, e.g., Read.¹¹ Energy levels of Ar^{4+} with the configuration [core] (4s nl), with nl = 4f, 5s, 5p are

thus estimated to be in the immediate vicinity of the double-capture channel with $Q = 26$ eV, whereas configurations like [core] (3d nl) seem to have energies near the $Q = 42$ eV double-capture channel. The widths of the two double-electron capture peaks are fairly large due to several close-lying capture levels and kinematic effects.

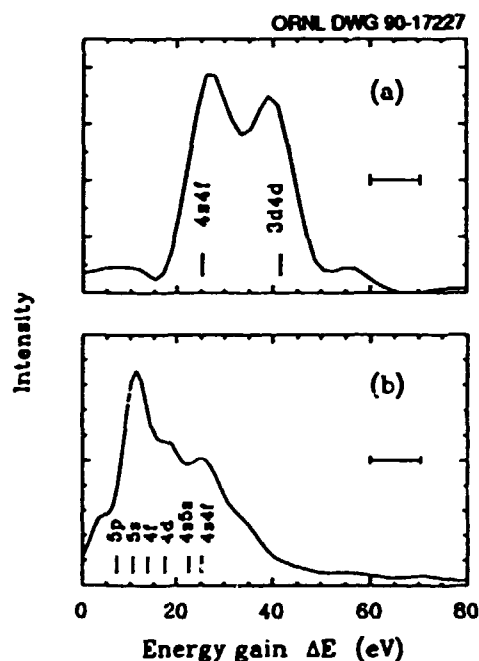


Fig. 5.9. Energy-gain spectra for double-electron capture (a) within projectile scattering angles of $5 \pm 2^\circ$, and single-electron capture (b) within $3 \pm 1.5^\circ$ in 450 eV Ar^{6+} - Ar collisions. The peak structure in (b) at higher energy gain values corresponds to a Q -value of 26 eV and is due to autoionization in one of the double-capture channels. The important electron capture channels are labeled. The horizontal bar indicates the energy resolution of the cylindrical analyzer.

In Fig. 5.10, the angular distribution of true double-electron capture [(a) dashed line] is compared to the distribution of single-electron capture [(a) solid line], and transfer ionization [(b) dashed line] at 450 eV. The true double-electron capture process is characterized by the transfer of two electrons from the target to a non-autoionizing projectile state, whereas the transfer ionization process involves the emission

of one electron from the projectile. The angular distribution of true double-electron capture shows a double-peak structure at large scattering angles (3.2° and 4.2°). Assuming direct (one-step) transitions between the initial and final channels one expects scattering angles at 1.7° and 2.5° for $Q = 26$ eV and $Q = 42$ eV, respectively. Instead, the peak at 3° can be explained by a mechanism involving two sequential one-electron transitions: the first one from the initial channel to either the 5s or the 4f state and the second one from capture of a second electron to the 4s state. Doubly excited 4s4f and 4s5s states could thus be formed with a Q -value of 26 eV. The corresponding rainbow scattering angles are observed in both the true double-electron capture and transfer ionization spectra at $\sim 3^\circ$. The $Q = 42$ eV channel which is seen only in the true double-electron capture spectrum is most likely populated through the diabatic 4d single-capture channel and its coupling to the 3d4d channel. The feature at about 6° is probably due to two-step population of the 3d4f and/or the 3d5s levels. Comparing the angular distribution of transfer ionization (b) in Fig. 5.10 with the angular distribution for true double-electron capture (a), we can conclude that the structure at smaller scattering angles of 3° is associated with a Q -value of 26 eV and the larger (4.2°) scattering angles with $Q = 42$ eV. Although both double-capture channels are energetically allowed to decay via autoionization, only transfer ionization states with Q -values close to 26 eV are observed. This is surprising, since one would expect a larger branching ratio for autoionization of excited states with a Q -value of 42 eV, because this requires the emission of an electron with lower energy than does the process for the $Q = 26$ eV channel. On the other hand, we have seen that states with high angular momentum components are populated in the two-electron capture process at $Q = 42$ eV. This might imply a low autoionization rate, due to weak interactions between electrons with high angular momentum. The ratio between the cross sections for true double-electron capture and transfer ionization is about 1.5 at 450 eV within our angular acceptance.

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7. R. K. Janev and H. Winter, *Phys. Rep.* **117**, 265 (1985).
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CONVOY ELECTRONS EMITTED FROM RESONANT COHERENTLY EXCITED IONS

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An axially channeled ion feels the anharmonic periodic potential of the crystal as an oscillatory electric field with a fundamental frequency $\nu = v/d$, where d is the atomic spacing and v the ion velocity. When the frequency (or a higher harmonic) coincides with an excitation energy of the ion, Resonant Coherent Excitation (RCE) can occur. This effect was first observed through the change in the charge state distribution of emergent ions,⁵ reflecting the higher probability for electron loss from resonantly excited states of projectile ions. Recently, Iwata *et al.*⁶ have observed photons emitted from excited states formed by RCE. In this work, we have made the first identification of a clear effect of RCE on convoy electron production.

A beam of C^{5+} ions from the ORNL EN Tandem accelerator was collimated by apertures of $0.3 \times 0.3 \text{ mm}^2$ and to a divergence angle less than 0.4 mrad and was incident upon gold (100) single crystal foil ($\sim 160\text{-nm}$ thick), mounted on a two-axis goniometer and placed at the entrance focus of an electrostatic spherical sector spectrometer ($\delta E/E @ 0.01$). The electrons emitted into a forward cone of half-angle $\theta_0 = 4.05^\circ$ were energy analyzed and detected by a microchannel plate (MCP). Carbon ions emerging from the crystal passed through an opening in the outer section of the spectrometer and were collimated by an aperture behind the spectrometer. The acceptance half-angle of the aperture was 1.8 mrad , which is about $1/7$ of the critical angle for (100) channeling of $20\text{-MeV } C^{5+}$ ions. Thus only well-channeled ions passing through the aperture were resolved into their charge states by an electrostatic analyzer and detected by a multidynode detector. Coincidences between convoy electrons and emergent ions of charge state q_e were registered by a time-to-amplitude converter (TAC).

Figure 5.11 shows a large enhancement of the yield of convoy electrons in coincidence with C^{6+}

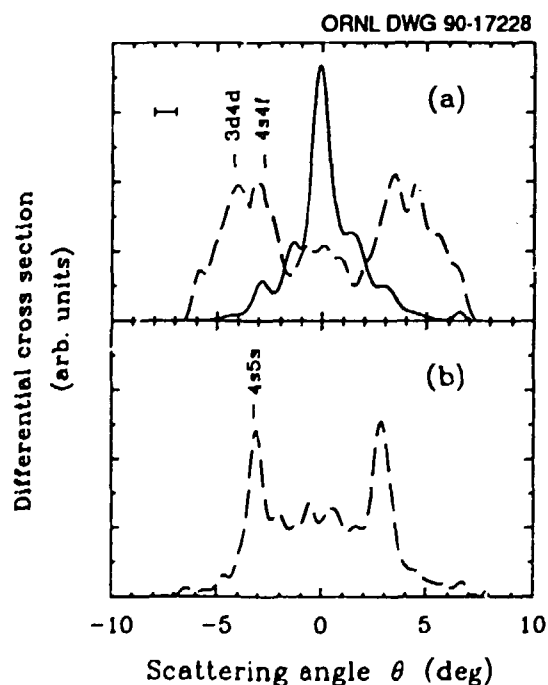


Fig. 5.10. Angular distribution for single-electron capture [(a), solid line], true double-electron capture [(a), dashed line] and transfer ionization [(b), dashed line] in $450 \text{ eV } Ar^{6+} - Ar$ collisions. The intensity of the single-capture peak is reduced by a factor of 10. The horizontal bar marks the FWHM of the incident Ar^{6+} - beam profile.

ions, traversing the $\langle 100 \rangle$ axis of 160-nm-thick Au crystals, normalized to the number of exit C^{5+} ions, as the incident velocity is swept through the second harmonic $1s - 2s$ and $2p$ (RCE) resonances near 20 MeV. A detailed rate-equation production model fit to the data, which includes separate treatment of the C^{5+} ground and excited state populations, reveals that while the fraction of all C^{5+} ions in the excited state is $\leq 1/3$, these excited ions contributed to $\geq 80\%$ of the convoy yield.

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5. S. Datz *et al.*, *Phys. Rev. Lett.* **40**, 843 (1978).
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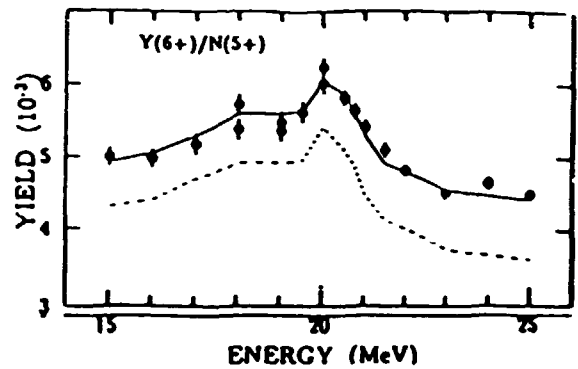


Fig. 5.11. Beam energy dependence of absolute convoy-electron yields measured in coincidence with exit C^{6+} ions, normalized to the number of exit C^{5+} ions. The solid line shows results of a model calculation for ELC, and the dashed line shows the calculated contribution from excited states.

ATOMIC PHYSICS FOR FUSION PROGRAM

MERGED-BEAMS STUDIES OF ELECTRON CAPTURE BY MULTIPLY CHARGED IONS AT LOW ENERGIES

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An ion-atom merged-beams apparatus is being used for the accurate quantitative study of very low-energy electron capture collisions (1-1000 eV/amu) of multiply charged ions with neutral atoms. Electrons of the temporary quasi-molecule formed in such collisions have sufficient time to adjust to the changing interatomic field as the nuclei approach and separate. Calculations in this regime require involved theoretical approaches which often disagree at these low energies.

Benchmark measurements with this unique apparatus have been compared with existing calculations, stimulating renewed theoretical interest in these low energy collisions. Recent merged-beams measurements² for $O^{3+} + H(D)$ support recent calculations³ that suggest the dominance of capture into the 3s state of the ion, and thereby resolve factor of three differences existing between calculations.^{3,4} Measurements² for $O^{4+} + H(D)$ are consistently lower than theory⁵ throughout the whole energy range, agreeing more with calculations that omit the expected enhancement due to rotational coupling. In these low-energy collisions, the attractive force due to the ion-induced dipole or polarization interaction between reactants may change reactant trajectories in such a way as to enhance the cross section for ion-neutral reactions. Merged-beams experimental data from this laboratory for $O^{3+} + H(D)$ are suggestive of such an enhancement.

During this last year the apparatus has been radically modified to increase sensitivity at the lowest energies and to increase angular collection. By shortening the merged path from 80 to 50 cm and increasing the diameter of collection lenses and beam pipes, the angular collection of the

$H(D)^+$ collision products has increased from an average of 1.8° to a minimum of 2.3° in the lab frame. As a result of these modifications, together with vacuum improvements in the merged section, the signal to background has been increased by at least a factor of three. With this large increase in sensitivity and angular collection, we plan to extend measurements to lower energies and to include ions with higher charge state. It is for such collisions that predicted effects due to the ion-induced dipole attraction may be evident. According to recent angular scattering calculations,⁶ this larger angular collection will be sufficient to resolve discrepancies between theory and experiment in the O^{3+} system for collision energies below 10 eV/amu.

We are assessing the feasibility to include the study of electron capture collisions with hydrogen atoms in highly excited Rydberg states, for which the cross sections are predicted to be enormous, and strong functions of the quantum number n as well as the charge of the multicharged ion. Collisions involving both high principal quantum numbers and high projectile charge states are still relatively unexplored. Cross sections for such collisions may prove to be the largest for any inelastic process involving atomic reactants.

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1. University of Tennessee, Knoxville.
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MERGED-BEAMS EXPERIMENT FOR ELECTRON-IMPACT EXCITATION OF IONS

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In addition to being of fundamental importance, electron-impact excitation of multiply charged ions is critical to radiative power loss and diagnostics of magnetic fusion plasmas. All excitation cross-section measurements for multiply charged ions have been based on the crossed-beams approach and on absolute intensity measurements of the radiation emitted as the excited states decay. Such measurements are severely limited by low photon intensities and detection efficiencies.

A novel experimental approach³ to this problem has been developed at the Joint Institute for Laboratory Astrophysics in Boulder, Colorado, for use in conjunction with the ORNL-ECR multi-charged ion source. In preparation for this experiment, modifications were made to the main beam line of the ORNL-ECR ion source, and the existing crossed-beams and merged-beams experiments were relocated. The new apparatus was moved to ORNL in January 1990.

The technique, illustrated in Fig. 5.12, involves merging fast beams of electrons and multiply charged ions in a uniform axial magnetic field, and detecting electron-impact excitation events via electron energy-loss spectroscopy. The beams are merged and demerged using trochoidal ($E \times B$) analyzers. The magnetic field ensures complete collection of inelastically scattered electrons, which are directed onto a position-sensitive detector. A fast two-beam modulation scheme is used to separate scattered electrons produced in beam-beam events from those due to interactions of either beam with residual gas or surfaces. To minimize background events, a vacuum of at least 1×10^{-10} torr is maintained with beams present. A moveable beam probe consisting of a phosphor screen and CID camera can be inserted into the interaction volume to quantify the three-dimensional spatial intensity distributions and overlap of the beams.

Absolute cross-section measurements for 3s-3p excitation of Na-like Si^{1+} are compared in Fig. 5.13 to 7-state close-coupling calculations by

Badnell, Pindzola, and Griffin, which have been convoluted with an experimental energy resolution of 0.2 eV. The agreement is seen to be very satisfactory. It is expected that improvements to the apparatus will permit the energy range of the method to be extended to several eV above the excitation threshold, where resonance effects are predicted to occur.

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3. E. Wählin et al., Abstracts, XVI ICPEAC, New York, 1989, p. 368.

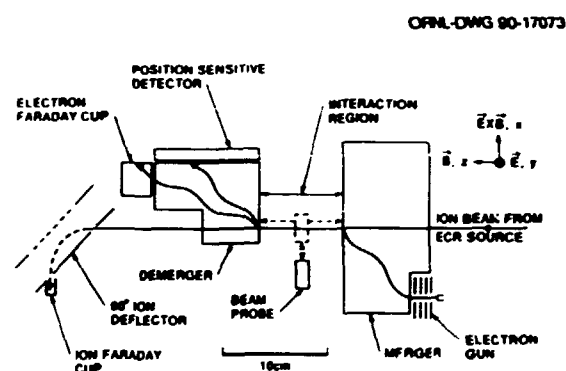


Fig. 5.12. Schematic of merged-beams electron energy loss apparatus.

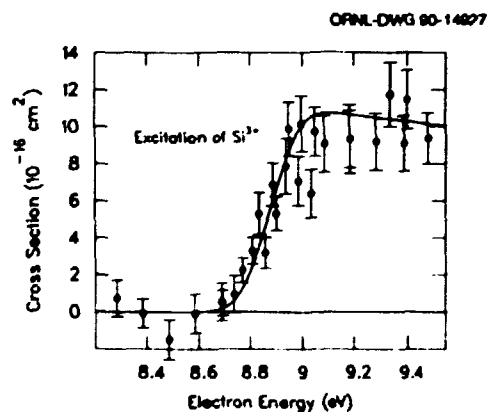


Fig. 5.13. Comparison of absolute cross-section measurements for 3s-3p excitation of Si^{1+} with 7-state close-coupling calculations by Badnell, Pindzola, and Griffin. The latter have been convoluted with a 0.2 eV FWHM Gaussian distribution to simulate the energy resolution of the experiment.

MEASUREMENT OF ELECTRON-IMPACT SINGLE IONIZATION CROSS SECTIONS FOR Ar^{18+}

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Measurements of electron-impact ionization cross sections for fusion-relevant ions have revealed much about the processes which contribute to net ionization. In addition to direct knock-off of an electron from the target ion, excitation of an inner electron will often result in an ionization event through autoionization. Other more exotic processes may also contribute to ionization, but an accurate evaluation of ionization and excitation-autoionization cross sections will most often prove adequate for the needs of plasma modelers. With numerous measurements and calculations with which to compare, and with more sophisticated codes, general trends have been recognized and have led to more accurate theoretical predictions.

One question which has remained difficult to answer concerns the metastable fraction expected for a given ionic species produced in a given ion source or plasma device. The physics of ionization of metastable ions may be quite different from that expected for ground-state ions, and the cross sections may be dramatically different in selected cases. Neon-like ions provide an especially informative test of our understanding of metastable ions. Based on a statistical mix of excited states, the metastable fraction is predicted to be small. Ionization from the ground state of such ions is predicted to be almost entirely due to direct ionization. Since a closed shell must be broken to produce an excited configuration, metastable energy levels lie significantly above the ground state. In addition, excitation-autoionization is expected to be quite strong from neon-like metastable ions. Thus, a double signature for metastable ions may be expected: an ionization threshold energy considerably lower than that of the ground-state ion, and significant excitation-autoionization contributions to the total ionization cross section.

Pindzola et al.² have compared their distorted-wave calculations with plasma rate measurements of limited accuracy and conclude that the conventional wisdom predicting a low metastable fraction for Ar^{18+} is justified. They also provide cross sections which can be compared with more

accurate and detailed measurements. In the present experiment, the ORNL electron-ion crossed beams apparatus has been used with the ORNL-ECR ion source to measure absolute cross sections for electron-impact ionization of neon-like Ar^{18+} . The results are shown in Fig. 5.14, compared with the calculations of Pindzola et al.² If the target ion beam were 100% metastable, the upper solid curve would describe direct ionization, while the total cross section including excitation-autoionization would follow the highest (dotted) curve off the graph, peaking at $2.2 \times 10^{-18} \text{ cm}^2$. A curve which is in good agreement with theory is obtained by assuming 5 to 7% metastable fraction.

In summary, the present results support a statistical model which predicts that low metastable fractions of neon-like ions should be produced in ion sources and plasma devices. This result is somewhat surprising since our experience has been that metastable fractions from "hot" ion sources are most often considerably higher than those predicted for a statistical mixture of state populations.

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2. M. S. Pindzola, D. C. Griffin, and C. Bottcher, Phys. Rev. A 41, 1375 (1990).

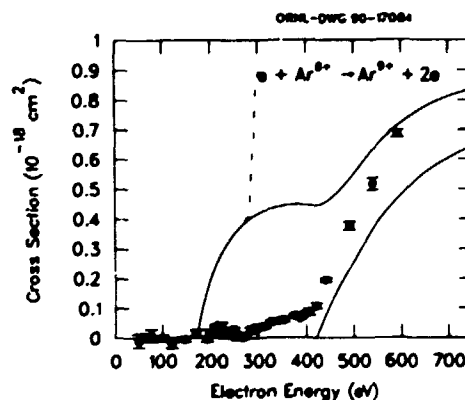


Fig. 5.14. Electron-impact ionization of Ar^{18+} . The points are present measurements, with relative uncertainties at the equivalent of one standard deviation. The curves are calculations from ref. 3: lower solid curve, ground-state direct ionization; upper solid curve, metastable direct ionization; dashed curve, metastable total ionization which peaks at 2.2, off scale.

MULTICHARGED ION-SURFACE INTERACTIONS

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We have continued our studies of neutralization of multicharged ions during grazing collisions with metal surfaces. Emphasis of this year's research was on the elucidation of the timescales over which projectile neutralization occurs. Our experimental approach was to study projectile K-Auger electron emission as a function of angle of incidence, i.e., as a function of the time the projectile spends in the vicinity of the surface.

Figure 5.15 shows the intensity variation of the N KLL Auger peak with angle of incidence for 60-keV N^{6+} projectiles on Au (110). Shown as an inset to this figure is the dependence of the 69-eV target (Au) peak on angle of incidence. This target transition arises as a result of vacancy transfer to one of the N shells of the Au target, and consequently gives further information on the projectile K-vacancy survival fraction at the time of surface penetration.

We have compared the experimentally determined K-Auger yields with those predicted by the frequently invoked Arifov model of multicharged ion neutralization. In this model, neutralization proceeds mainly via quasi-resonant multi-electron transfer from the metal valence band to high n Rydberg levels of the projectile, forming multi-excited unstable states, which relax by a complex autoionization cascade. We made a computer simulation³ of this autoionization cascade using calculated atomic Auger transition rates. On the basis of this simulation, we conclude that the autoionization cascade is much too slow to explain the observed K-Auger yields. The cascade is assumed to start at $30 a_0$ above the surface with 6 resonantly captured electrons in the $n=7$ shell of the projectile. Re-neutralization into $n=7$ is assumed subsequent to each autoionization step. In order to obtain the experimentally observed K-Auger yield, a rapid filling of the projectile L-shell starting at $8 a_0$ above the surface had to be invoked, suggesting the possible importance of Auger de-excitation processes in the

immediate vicinity of the surface in multicharged ion neutralization.

Recently, we initiated an investigation of the extent to which electron emission from below the surface can also contribute to the observed projectile K-Auger peaks. Using a Monte-Carlo simulation of the angular scattering and straggling of the projectile occurring inside the bulk, we obtained estimates of the contributions to the observed projectile K-Auger peak of electron emission below the surface, as well as emission on the outgoing trajectory for those particles that have been reflected. For angles of incidence much below 5° , the results of these simulations indicate significant contributions by projectiles that have been reflected. We also calculated model line-shapes of projectile K-Auger emission after surface penetration by taking into account the Doppler shift of the scattered ions prior to Auger emission.

1. Chemistry Division, ORNL.
2. Solid State Division, ORNL.
3. P. A. Zeijlmans van Emmichoven, C. C. Havener, and F. W. Meyer, "The Neutralization of Highly Charged Ions Grazingly Incident on a Metal Surface," to be published in *Physical Review A*.

ORNL-DWG 80-13108

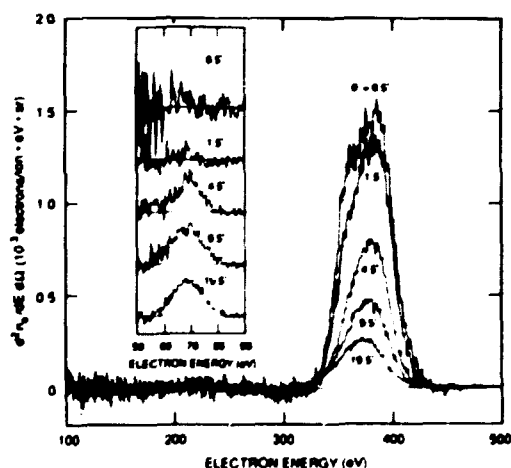


Fig. 5.15. Dependence of the normalized projectile KLL and target NVV Auger electron intensity on the angle of incidence for 60-keV N^{6+} ions incident on Au(110).

POST-COLLISION EFFECTS IN AUGER EMISSION

J. K. Swenson¹ C. C. Havener
J. Burgdorfer² D. C. Gregory
F. W. Meyer N. Stolterfoht³

When a doubly excited atom produced in a low-energy ion-atom collision decays by Auger electron emission, there can be considerable interaction of the emitted electron with the nearby charged collision partner. Recently, we reported on a new aspect of this postcollisional interaction (PCI), namely, the deflection of the ejected electrons in the Coulomb field of the receding spectator ion. For 2- to 15-keV $\text{He}^+ + \text{He}$ collisions, we observed that these deflections resulted in a "Coulomb focussing" of the emitted electrons near the beam axis.⁴

During follow-up investigations of this effect, in which electron spectra were measured at various angles near the beam axis, we observed electron emission lineshapes, especially that due to $2s^2^1S$, that showed not only the usual PCI broadening but also significant structure which exhibited an uncharacteristic rapid angular dependence and, like Coulomb focusing, was limited to electron emission close to the beam axis. We were able to explain the observed lineshapes in terms of a new PCI phenomenon, namely Coulomb "path" interference⁵ resulting from the existence of two trajectories, indistinguishable with respect to laboratory energy and emission angle, along which ejected autoionizing electrons may be scattered by the attractive Coulomb potential of the slowly receding spectator ion. In order to calculate the effect of Coulomb interference on the observed lineshape, a semiclassical model was developed in which we account for the phase difference between the two different trajectories the emitted electron can follow subsequent to autoionization of the autoionizing state. Our model is a simple extension of the previously used "overlapping resonances" model⁶ using the WKB approximation for scattering in a central field. Figure 5.16 shows that calculated model lineshapes (solid lines), which include contributions from adjacent overlapping resonances, are found to be in excellent agreement with the angular dependence observed in 10 keV $\text{He}^+ + \text{He}$ spectra. Also shown in Fig. 5.16 are calculations (broken lines) using the model of overlapping resonances without Coulomb interference. As can be seen, these lineshapes do

not exhibit the observed interference structure in the $2s^2^1S$ lineshape.

In order to illustrate the effect of Coulomb interference alone, we show in Fig. 5.17 the interference lineshape for an isolated $2s^2^1S$ resonance. Such an isolated line does not exist in our current collision system, but, as seen in the figure, observation of such a line would provide a clear signature of Coulomb interference and would provide for a more detailed test of our modelling.

1. Lawrence Livermore National Lab., Livermore, CA.
2. University of Tennessee, Knoxville.
3. Hahn-Meitner Institut für Kernforschung GmbH, Berlin, Germany.
4. J. K. Swenson et al., *Phys. Rev. Lett.* **63**, 35 (1989).
5. J. K. Swenson et al., submitted to *Physical Review Letters*.
6. R. Morgenstern, A. Niehaus, and U. Thielman, *J. Phys. B* **10**, 1039 (1977).

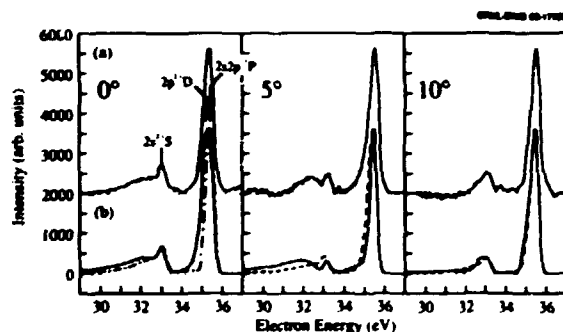


Fig. 5.16. (a) He target autoionizing spectra obtained following 10 keV $\text{He}^+ + \text{He}$ collisions. (b) Calculated lineshapes with (solid) and without (broken curve) Coulomb interference.

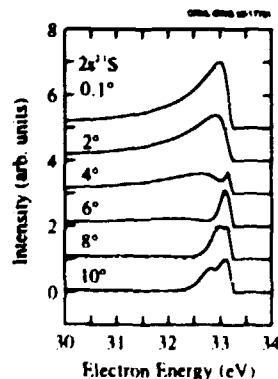


Fig. 5.17. Calculated lineshapes for an isolated $2s^2^1S$ state evaluated at various emission angles including Coulomb interference.

ECR ION SOURCE UPGRADE

F. W. Meyer

Design studies for an upgraded version of the existing ORNL ECR source were completed this year. The upgrade version is very similar in overall mechanical design to the 10.6-GHz ORNL ECR source, will operate at 14.5 GHz, and will feature an iron return yoke for the axial magnetic field coils. The 14.5-GHz ORNL ECR source is shown schematically in Fig. 5.18. Use of an iron flux return circuit will give about a 20% increase in axial magnetic field intensity; the increased power dissipation associated with the remaining 20% increase in axial magnetic field required to attain a closed ECR surface at 14.5 GHz can be handled easily by the cooling capacity reserves designed into the present coils. The permanent magnet hexapole structure can also be easily upgraded for 14.5-GHz operation by replacing the original SmCo₅ material with Nd-Fe-B magnets, which will produce about 40% higher peak magnetic fields.

The use of a higher microwave frequency is expected to significantly increase extracted beam currents, especially for charge states above the peak of the extracted charge state distribution. The dashed lines in Fig. 5.19 show the expected charge-state trend vs atomic mass number of the ionic species for two different beam intensities at 14.5 GHz based on recent measurements on the 14.5-GHz MINIMAFIOS source at Grenoble. For comparison, Fig. 5.19 also shows the corresponding curves describing the performance of the present 10.6-GHz ECR source. The expected performance at 14.5 GHz for Au ions is shown in Fig. 5.20 by the dashed line; charge state distributions for Au and other metallic beams obtained with the present 10.6-GHz ECR source are also shown for comparison.

The improved performance of the new 14.5-GHz ECR source, both in forms of increased beam intensity and significantly higher charge states, will not only facilitate current measurements of atomic collision processes involving multicharged ions, but also permit new investigations that are technically not feasible with the existing ECR source.

OPNL-DWG 88M-14804

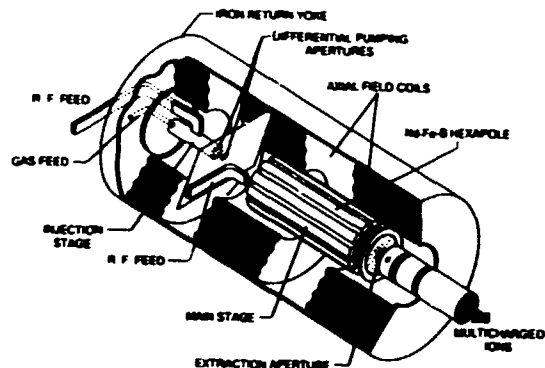


Fig. 5.18. Proposed 14.5-GHz ECR ion source.

CPNL-DWG 85M-18100

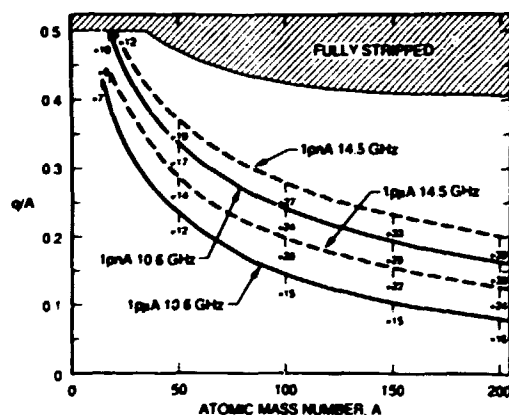


Fig. 5.19. Expected performance of the planned 14.5-GHz ORNL ECR source — dashed lines. The solid lines are corresponding curves for the existing 10.6-GHz ECR source.

CPNL-DWG 884-14803

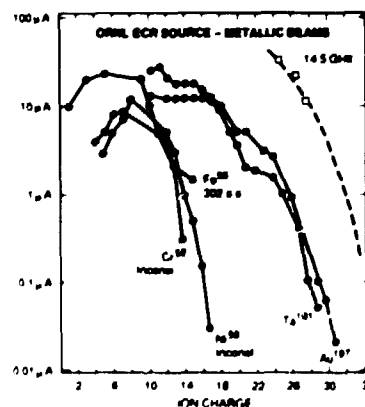


Fig. 5.20. Expected performance of the planned 14.5-GHz ORNL ECR source for Au ions (dashed line) compared with present performance (solid lines).

6. LASER AND ELECTRO-OPTICS LAB

ATF MULTICHANNEL INTERFEROMETER

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L. R. Baylor¹ M. Murakami²
M. J. Crouse² K. L. Vander Sluis
J. B. Wilgen³

During the past year, simultaneous measurements of electron density have been achieved on seven channels of the FIR interferometer system on the Advanced Toroidal Facility (ATF). The number of simultaneous channels available was limited by availability of Schottky-diode detectors. Details of the system have been reported.⁴

The system has been reliably employed to study density evolution in ECH as well as neutral-beam-heated plasma discharges with gas fueling and pellet injection. A chordal inversion code has been developed, and has been used successfully to reconstruct the spatial distribution of electron density in ATF. The code has been employed routinely to provide density profile information for ATF plasma studies, including 20-second plasma pulse operations and bootstrap current studies. Figure 6.1 shows the time-resolved traces of the line-integrated electron density of a neutral-beam-heated plasma discharge. During this discharge, a solid hydrogen pellet was injected into the plasma at a time of approximately 356 ms after the beginning of the discharge. The abrupt changes of the line densities occur during a period of approximately 0.2 ms. The inverted density profile of this discharge is shown in Fig. 6.2. The density profile became extremely peaked as a result of the injection. Arrangement has been made to acquire more Schottky-diode detectors, and simultaneous measurements of electron density on twelve channels are expected in the near future.

1. Engineering Division, ORNL.
2. University of Tennessee, Knoxville.
3. Fusion Energy Division, ORNL.
4. C. H. Ma, D. P. Hutchinson, and K. L. Vander Sluis, *Rev. Sci. Instrum.* 61, 2891-2 (1990).

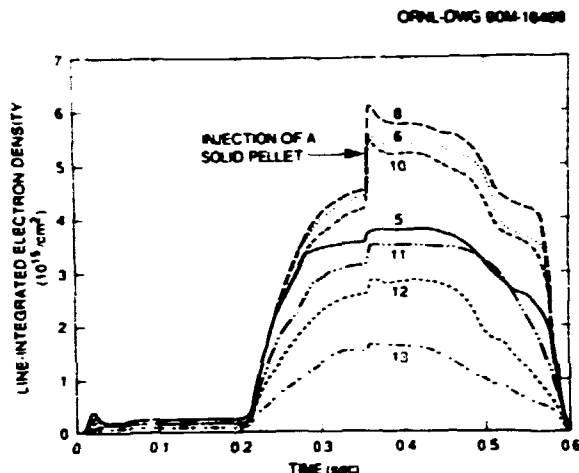


Fig. 6.1. Time variations of the line-integrated electron density measured by the multichord FIR interferometer system on ATF. The abrupt changes of the line-density are caused by the injection of a solid hydrogen pellet approximately 356 ms after the beginning of the discharge.

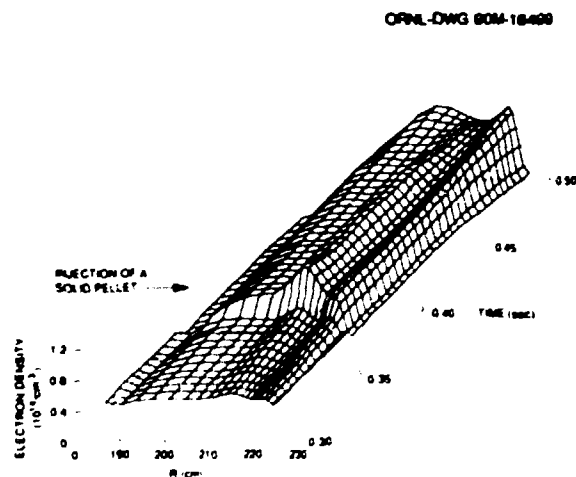


Fig. 6.2. Inverted density profile from the discharge discussed in Fig. 1. The density profile became extremely peaked as a result of the pellet injection.

SMALL-ANGLE CO₂ LASER THOMSON SCATTERING DIAGNOSTIC FOR D-T FUSION PRODUCT ALPHA PARTICLES

R. K. Richards¹ H. T. Hunter
C. A. Bennet¹ D. P. Hutchinson
K. L. Vander Shuis

A diagnostic is currently under development for the measurement of D-T fusion product alpha particles. In a fusion reactor the slowing of these particles on the background plasma maintains an energy input needed to sustain fusion ignition. The energy exchange between the alpha particles (which originate at 3.5 MeV) and the background plasma (typically at 10 keV) can be determined by the shape of the alpha particle velocity distribution. To measure this velocity distribution, a CO₂ laser Thomson scattering diagnostic system is being investigated. This measurement requires a high power laser source and detection of scattered radiation at very small angles, around 1°. The small angles are required to reduce the scattering from the background electrons but present a problem in detection of small signals in the presence of a large stray light background.

To test the feasibility of performing small-angle scattering measurements, a proof-of-principle test is currently in progress. The tests are being conducted on a nonburning plasma experiment, the Advanced Toroidal Facility (ATF) with the scattering from background electrons. A schematic of the experiment is given in Fig. 6.3.

To reduce the effects of the stray laser radiation and improve the signal-to-noise ratio, heterodyne detection is employed with the local oscillator set between the normal wavelengths of the CO₂ source laser. Stray radiation is further reduced with a hot CO₂ absorption cell in the detector system. This cell reduces radiation at the laser source wavelength by a factor of 67,000 while reducing the signal at the local oscillator wavelength by only 10%.

The optical system was tested during plasma operation on ATF for changes in the alignment and no problems were found.

An in-situ calibration system was installed, which allowed a real-time monitor of the system efficiency that was found to remain constant during plasma operation.

Tests were conducted on the pulsed laser system. With injection by a cw laser the pulsed CO₂ laser was found to produce 1 μ s, 5 J pulses — adequate for the scattering experiment. The injector laser was capable of controlling the mode and wavelength of the pulsed laser. With the optical path of the low power cw laser coincident with the high power pulsed laser, alignment and drift of the small scattering angle was monitored with the cw laser.

Tests of the pulsed laser produced damage to the anti-reflection coatings on the vacuum windows for ATF. This problem was eliminated by replacing the coated windows with Brewster-angle windows. After a series of test shots, no damage was observed on the new windows.

A computer system has been set up which allows remote control of the pulsed laser, data retrieval and analysis, and continuous monitoring of the system alignment and calibration.

1. Fusion Energy Division, ORNL.
2. University of North Carolina, Asheville.

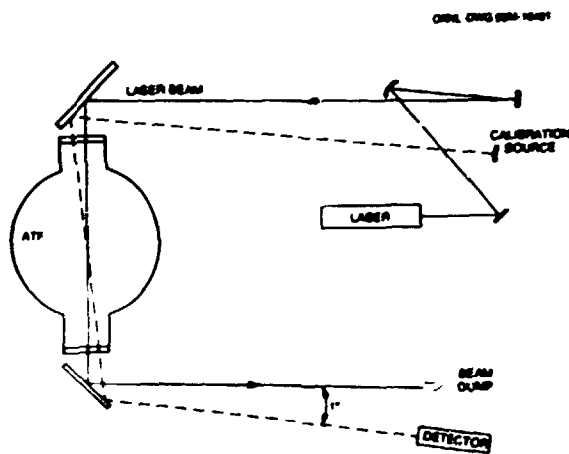


Fig. 6.3. Schematic of the proof-of-principle test on ATF for the small-angle CO₂ laser Thomson scattering diagnostic.

ANOMALOUS THERMAL EFFECTS IN DEUTERATED METALS

D. P. Hutchinson C. C. Havener
C. A. Bennett¹ R. K. Richards²

During the past year we have continued to study the anomalous excess energy production in electrolysis cells associated with the reported "cold fusion" results of Pons and Fleischmann. In FY-1989, four calorimetry cells were constructed to study the energy balance of electrolysis cells using palladium cathodes, platinum anodes in a 0.2-M LiOD electrolyte. The cells had no internal recombination and the energy balance was established by measuring the heat flow from the cells to a temperature-controlled bath through a Teflon barrier. A different palladium cathode preparation was used for each cell. As reported earlier,³ one of the cells demonstrated an anomalous heat imbalance of 2 to 3 W for a period of approximately 300 hours. During FY-1990, we constructed four new experiments in an effort to reproduce and investigate this result.

The palladium cathodes of the four new experiments were fabricated from 6.35-mm-diam by 100-mm-long rods annealed in vacuum at a temperature of 900°C for four hours. This duplicated the preparation of the electrode of the first cell that exhibited excess heat. These new cells contained an internal heater for initial calibration of the experiments as well as periodic recalibration to monitor the accuracy of the measurement. Three platinum resistance temperature detectors (RTD) were placed around each cell to measure the heat flow to the temperature-controlled water bath. Duplicating the conditions of the first cell that demonstrated excess heat production, the new experiments were precharged at a low current density of 50 mA/cm² for over 100 hours. The current density was then increased to 250 mA/cm². All four cells produced excess heat ranging from 2 to 8.6 W. The cell current was then varied between 50 and 250 mA/cm² and it was determined that the excess power was proportional to current density. One of the cells was converted to light water and the excess heat was observed to disappear. We operated these four cells for a total time of 2000 hours

and the integrated excess energy output averaged 20 megajoules/cell.

Several new experiments are planned for the coming year using a flow calorimeter with internal recombination and several different electrode designs to further investigate this phenomena.

-
1. University of North Carolina, Asheville.
 2. Fusion Energy Division, ORNL.
 3. D. P. Hutchinson, C. A. Bennett, R. K. Richards, J. S. Bullock IV, and G. L. Powell, *Initial Calorimetry Experiments in the Physics Division-ORNL*, ORNL/TM-11356, Oak Ridge Natl. Lab., Martin Marietta Energy Systems, Inc., May 1990.

7. THEORETICAL PHYSICS

COHERENT ELECTROMAGNETIC PRODUCTION OF MU AND TAU LEPTON PAIRS IN RELATIVISTIC HEAVY-ION COLLISIONS¹

C. Botcher and M. R. Strayer

We calculate the coherent production of muon and tauon pairs in peripheral collisions between nuclei at ultrarelativistic energies. This type of production exhibits a high degree of sensitivity to the electromagnetic structure of the nucleons in the colliding nuclei. The pair cross sections, even at high invariant mass, and transverse momenta, are large on hadronic scales, and are governed by the magnitude of the nuclear and nucleon form factors at momentum transfers greater than 1 GeV/c. We argue that this process could serve as a useful experimental probe of nuclear and nucleon form factors.

1. Abstract of paper: *J. Phys. G* 16, 975 (1990).

COHERENT HIGGS PRODUCTION AT HEAVY-ION COLLIDERS¹

*J. S. Wu², C. Botcher, M. R. Strayer,
A. K. Kerman³*

Cross sections for the coherent production of the Higgs boson in ultrarelativistic heavy-ion collisions are calculated by the direct Monte Carlo evaluation of Feynman integrals. This approach is particularly well suited to study the production and decay products with tagged nuclear states. Distributions in impact parameters are calculated. We find that excluding the central impact parameter region of the collision reduces the production cross section by approximately a factor of two for an intermediate mass Higgs with Pb beams at the proposed Large Hadron Collider (LHC).

1. Abstract of paper: *Particle World* 1, 153 (1990).

2. Consultant from University of Tennessee, Knoxville.

3. M.I.T., Cambridge, MA.

CALCULATING COHERENT PAIR PRODUCTION WITH MONTE CARLO METHODS¹

C. Botcher and M. R. Strayer

Calculations of the coherent electromagnetic pair production in ultrarelativistic hadron collisions are discussed. This type of production, in lowest order, is obtained from tree diagrams which contain two virtual photons. Simple Monte Carlo methods for evaluating these classes of diagrams without recourse to involved algebraic reduction schemes are discussed.

1. Abstract of paper: pp. 118-153 in *Proceedings of the Summer School of Computational Atomic and Nuclear Physics*, Sewanee, TN 1989, World Scientific Publishing Co., Singapore (1990).

COHERENT PARTICLE PRODUCTION IN A CLASSICAL FIELD APPROXIMATION¹

J. S. Wu², C. Botcher, M. R. Strayer

A classical field approximation for the coherent production of particles via two-photon processes is derived and related to the same result obtained with quantum field theory. It is shown that the two approaches give identical results whenever the frequency of the virtual photons is small compared to available energy, as is the case in ultrarelativistic heavy-ion collisions.

1. Abstract of paper to be published in *Physics Letters B*.

2. Consultant from University of Tennessee, Knoxville.

COHERENT PARTICLE PRODUCTION FROM RELATIVISTIC HEAVY-ION COLLISIONS¹

*J. S. Wu², C. Boucher, M. R. Strayer, D. J. Ernst³,
A. K. Kerman⁴*

The production of charged vector boson pairs from the coherent electromagnetic field of colliding nuclei is calculated within the framework of a classical field approximation. The approximation is derived for both lepton and boson pairs in terms of two-photon Feynman diagrams.

1. Abstract of paper to be published in *Proceedings of 2nd International Conference on Medium- and High-Energy Nuclear Physics, Taiwan, Republic of China, May 8-12, 1990.*

2. Consultant from University of Tennessee, Knoxville.

3. Consultant from Texas A&M University, College Station.

4. M.I.T., Cambridge, MA.

COHERENT HIGGS AND $W^\pm$ PAIR PRODUCTION¹

*J. S. Wu², C. Boucher, M. R. Strayer,
A. K. Kerman³*

Cross sections for the coherent electromagnetic production of the intermediate vector bosons and the Higgs boson in ultrarelativistic heavy-ion collisions are calculated from standard electroweak theory. The distributions of the resulting decay products are also considered. Particular attention is given to the energy régime of the Superconducting Supercollider (SSC) and the CERN Large Hadron Collider (LHC).

1. Abstract of paper submitted to *Annals of Physics*.

2. Consultant from University of Tennessee, Knoxville.

3. M.I.T., Cambridge.

SPIN EFFECTS IN TWO-PHOTON PAIR PRODUCTION¹

*C. J. Albert², D. J. Ernst², C. Boucher
M. R. Strayer*

The two-photon mechanism for lepton pair production is investigated. It is found that for pairs produced in certain kinematical regions the process is dominated by magnetic, spin-flip currents. Anomalous e^+e^- pairs observed in 17 GeV/c pion-proton collisions are found to be predominantly produced by this spin-flip mechanism. A comparison between $^4\text{He} + ^4\text{He}$ collisions and $^3\text{He} + ^4\text{He}$ collisions is proposed as an experimental way of distinguishing between the electric, nonspin-flip mechanism and the magnetic, spin-flip mechanism.

1. Abstract of paper to be published in *Proceedings of 2nd International Conference on Medium- and High-Energy Nuclear Physics, Taiwan, Republic of China, May 8-12, 1990.*

2. Texas A&M University, College Station.

BASIS-SPLINE COLLOCATION METHOD FOR THE LATTICE SOLUTION OF BOUNDARY VALUE PROBLEMS¹

*A. S. Umar², J. Wu³, M. R. Strayer,
C. Boucher*

A particular utilization of the Basis-Spline Collocation Method (BSCM) for the lattice solution of boundary value problems is studied. The implementation of a general set of boundary conditions is demonstrated. Among the selected problems are the Schrödinger equation in radial coordinates, the Poisson and the generalized Helmholtz equations in radial and three-dimensional Cartesian coordinates.

1. Abstract of paper to be published in *Journal of Computational Physics*.

2. Consultant from Vanderbilt University, Nashville, TN.

3. Consultant from University of Tennessee, Knoxville.

THE BASIS SPLINE METHOD AND ASSOCIATED TECHNIQUES¹

C. Boucher and M. R. Strayer

The basis spline and collocation methods for the solution of partial differential equations are outlined. Particular attention is paid to the theory of errors and the handling of non-self-adjoint problems which are generated by the collocation method. Applications to Poisson's equation, the Dirac equation, and the calculation of bound and continuum states of atomic and nuclear systems are discussed.

1. Abstract of paper: pp. 217-240 in *Proceedings of the Summer School of Computational Atomic and Nuclear Physics*, Sewanee, TN, 1989, World Scientific Publishing Co., Singapore (1990).

FRAGMENTATION OF A FINITE-MASS STRING¹

Cheuk-Yin Wong and Ren-Chuan Wang²

The iterative Lund model, which uses a splitting function independent of the coordinates of the end vertices of the fragmenting string or substring, is, in fact, an outside-inside cascade model of string fragmentation, in contradistinction from the inside-outside cascade picture of Bjorken. To bring out the salient features of the inside-outside cascade picture, we introduce alternative string fragmentation models in which the space-time distributions of the vertices are parametrized explicitly in terms of their space-time coordinates measured from the point of the onset of separation of the quark and the antiquark. An iterative procedure is obtained to fragment a finite string into hadrons. The rapidity distributions obtained from the new models and the iterative Lund model are compared.

1. Abstract of paper submitted to *Physical Review D*.

2. University of Science and Technology of China, Hefei, Anhui Province, China.

STUDY OF PARTICLE PRODUCTION USING BOSONIZED QED²¹

Cheuk-Yin Wong, Ren-Chuan Wang²,
Chia C. Shih³

Particle production is an important process in high-energy, e^+e^- hadron-nucleus and nucleus-nucleus collisions. It is related to the dynamics of hadronization, the possible formation of a quark-gluon plasma, the energy released in a nucleus-nucleus collision and the nuclear stopping power. It is of interest to study the physics of particle production with QCD-inspired, low-dimensional, nonperturbative models. The two-dimensional massless quantum electrodynamics^{4,5} in one space coordinate and one time coordinate (QED2) furnishes an interesting arena for such a study. It is a system in which a neutral boson exists as a nonperturbative bound state.^{4,5} When a positive and negative charge pair are separated in such a system, the vacuum is so polarized that the positive charge and the negative charge are completely screened in a manner similar to the confinement of quarks. The rapidity distribution of the produced particles in a system of two opposite charges, pulling apart at high relative energies, will exhibit a plateau structure in rapidity essentially in agreement with the experimental shape of the rapidity data at high energies.

From the work of Schwinger,⁴ it is known that QED2 involving massless fermions and electromagnetic interactions is equivalent to a field ϕ of free massive bosons. There is a connection between the bosonic pseudoscalar field and the fermionic currents j^μ . The dynamics of the system can be represented as the evolution of the massive pseudoscalar field which can be obtained from the initial values data of the fermionic currents.

From the field quantities, we find the momentum distribution of the bosons as given by

$$\frac{dN}{dp^1} = \frac{\pi}{2p^0 e^2} \left[\frac{p^0}{p^1} \bar{j}^0(p^1) + \bar{j}^1(p^1) \right] \\ \times \left[\frac{p^0}{p^1} \bar{j}^0(-p^1) + \bar{j}^1(-p^1) \right],$$

and the rapidity distribution of the particles is

$$\frac{dN}{dy} = \frac{\pi}{2e^2} \left[\frac{p^0}{p^1} \tilde{j}^0(p^1) + \tilde{j}^1(p^1) \right] \left[\frac{p^0}{p^1} \tilde{j}^0(-p^1) + \tilde{j}^1(-p^1) \right],$$

where $\tilde{j}^\mu(p^1)$ is the Fourier transform of $j^\mu(x, t=0)$:

$$\tilde{j}^\mu(p^1) = \frac{1}{\sqrt{2\pi}} \int dx e^{-ip^1 x} j^\mu(x, 0).$$

As a simple example, we study the case of a positive charge $+ve$ pulling away from a negative charge $-ve$ with a center-of-mass energy $\sqrt{s}$, to simulate approximately the dynamics as a quark pulls away from an antiquark after an electron annihilates with a positron. We obtain

$$\frac{dN}{dy} = \frac{v^2 \xi^2}{\sinh^2 \xi},$$

where

$$\xi = \frac{v^2 \pi^2 m \sinh y}{3\sqrt{s}}.$$

The rapidity distribution has a plateau near $y \sim 0$. In the limit of very large energies, the rapidity distribution is $dN/dy = v^2$, which agrees with that of Casher *et al.*⁵ (for $v=1$), and our pseudoscalar field agrees (up to a normalization factor) with the pseudoscalar field of Casher *et al.*⁵. It would be appropriate in future work to study the dynamics with QCD2, which has been found to be a good approximation to QCD for mesons in the large N approximation.⁶ We are investigating this topic at present.

1. Summary of paper submitted to *Physical Review D*.

2. University of Science and Technology of China, Hefei, Anhui, China.

3. Guest Assignee from University of Tennessee.

4. J. Schwinger, *Phys. Rev.* 128, 2425 (1962); J. Schwinger, p. 89 in *Theoretical Physics*, Trieste Lectures, 1962 (I.A.E.A., Vienna, 1963).

5. A. Casher, J. Kogut, and L. Susskind, *Phys. Rev. D* 10, 732 (1974).

6. G. 'tHooft, *Nucl. Phys.* B72, 461 (1974); G. 'tHooft, *Nucl. Phys.* B75, 461 (1974).

FEATURES OF PARTICLE PRODUCTION FROM A CLASS OF SIMPLE BRANCHING MODELS¹

Chia C. Shih² and Cheuk-Yin Wong

It has been shown recently that in particle production processes a cascade of massive clusters into smaller clusters at each branching may exhibit power-law behavior.³⁻⁵ Normally a cascade mechanism may also have definitive predictions in other characteristics of the multiparticle production process. It is therefore interesting to investigate other features of this kind of cascade model.⁶

Following Chiu and Hwa,⁵ we examined three different kinds of splitting functions, $P(z)$, which give the probability for one daughter a (of energy e' , momentum p') having a fraction z_a of its parent's light-cone momentum defined by

$$z_{\pm} = \frac{e' \pm p'}{e \pm p}$$

and the momentum fraction of the other daughter is then $z_b = 1 - z_a$. The choice of either $+$ or $-$ at each vertex of branching is random. The splitting functions are:

I. Gluon model:

$$P(z) = c((1-z)/z + z/(1-z) + z(1-z)),$$

II. ϕ^3 model:

$$P(z) = 6z(1-z),$$

III. twin model:

$$P(z) = \delta(z-1/2).$$

Using q^2 for the virtuality (invariant mass) for the massive clusters, we then introduce a joint probability distribution function $S(q_a^2, q_b^2)$ (Sudakov form factor) as follows:⁷ For a given value of z , the probability element for the occurrence of the invariant virtualities of the two daughters q_a^2 and q_b^2 is given by

$$S(q_a^2, q_b^2; q^2) dq_a^2 dq_b^2 \sim \delta(q^2 - q_a^2/z_a - q_b^2/z_b) dq_a^2 dq_b^2 \cdot \exp[-c(q^2) \ln(q_{a,\max}^2/q_a^2) \ln(q_{b,\max}^2/q_b^2)]$$

with

$$c(q^2) = \frac{3}{33-2\pi\alpha} \ln(q^2/\Lambda^2),$$

where the $q_{a,\max}$, $q_{b,\max}$ are the kinematic limits of the corresponding variables. The δ -function constrain comes from the conservation of energy momentum. In this fashion, the symmetry between the two daughters and the conservation of energy and momentum is explicitly built in at each step of branching. By considering the light-cone variables and exact energy momentum consideration at each branching step, we can insure the conservation of total energy and momentum relating the initial state and the final products. We are able to create a nearly symmetrical rapidity plateau and examine each model for many special features. It enables us to study some general features of the distributions of produced particles such as the inclusive rapidity plateau, "intermittency" characteristics, nonstationary effects in correlation, and forward-backward correlations, as a function of the collisional energy $\sqrt{s}$.

1. Summary of paper to be published in *Proceedings of Workshop on Intermittency in High-Energy Collisions*, Santa Fe, NM, March 1990.

2. Guest Assignee from University of Tennessee.

3. A. Bialas and R. Peschanski, *Phys. Lett.* 207, 59 (1988).

4. W. Ochs and J. Wosiek, *Phys. Lett.* 214B, 617 (1988).

5. C. Chiu and R. Hwa, University of Texas preprint (1989) to be published in *Physics Letters B*.

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RELATIVISTIC EFFECTS IN $\gamma\gamma$ DECAYS OF P-WAVE POSITRONIUM AND $q\bar{q}$ SYSTEMS¹

Z. P. Li², F. E. Close³, T. Barnes⁴

Theories of the two-photon couplings of P-wave positronium and $q\bar{q}$ systems are reviewed and a relationship is found between field theoretic calculations of $q\bar{q} \rightarrow \gamma\gamma$ and the Vector Meson

Dominance (VMD) model for both heavy and light quark systems. Relativistic corrections to the two-photon decay rates are evaluated, and are found to be very important for the light quark system. We find that the widely quoted ratio of 15/4 between the $\gamma\gamma$ widths of heavy-quark scalar and tensor mesons is significantly modified in the light $q\bar{q}$ sector. We find, however, that the helicity-zero amplitude for the $\gamma\gamma$ coupling of the tensor mesons, which vanishes in the nonrelativistic limit, remains small for light quarks in accord with experimental observation.

1. Abstract of paper to be published in *Physical Review D*.

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TWO-PHOTON DECAYS OF QUARKONIUM STATES

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The subject of two-photon production of meson resonances is a very active area in both experimental and theoretical hadron spectroscopy. This production mechanism is accessible to e^+e^- machines, and as the coupling of the photon to quarks is relatively well understood, it offers a clean test of possible quark model assignments of various problematic meson states. Examples include the S^* and δ ($f_0(975)$ and $a_0(983)$) resonances, which are now widely believed to be $K\bar{K}$ bound states; their $\gamma\gamma$ couplings are smaller than quark model predictions for $q\bar{q}$ states by an order of magnitude.

A problem with the theoretical predictions of $\gamma\gamma$ - $q\bar{q}$ couplings is that they are typically carried out in the nonrelativistic limit, and relativistic corrections may actually be important. We have calculated the $O(v^2/c^2)$ relativistic correction to the helicity amplitudes and total widths of 0^{++} and 2^{++} states,⁴ and find that the well-known ratio 15/4 for their total widths is reduced to about 2 by relativistic corrections. (The dominance of the helicity-2 amplitudes in 2^{++} decay, however, is still a good approximation in the relativistic treatment.) We also establish a relation

between these quarkonium calculations and the vector meson dominance model, which superficially appears to be an unrelated approach.

1. UT-ORNL Collaborative Scientist.
2. UT-ORNL Distinguished Scientist.
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4. Z. P. Li, F. E. Close, and T. Barnes, ORNL-CCIP-90-04, to be published in *Physical Review D*.

RELATIVISTIC TRANSPORT THEORY OF FLUCTUATING FIELDS FOR HADRONS¹

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We analyze the physics of relativistic nuclear collisions and demonstrate that an adequate treatment of pions must include the quantum time-energy uncertainty principle and nonsequential three-body collisions. We apply relativistic quantum field theory to obtain exact equations determining the time evolution of hadronic fields and their fluctuations in terms of the effective interactions describing scattering in matter. These equations relate the main physical observables to the sought-after properties of nuclear matter, and involve only these quantities and the corresponding properties of free-space one- and two-body processes. We show how to regularize the singularities by employing the internal structure of the mesons, while maintaining causality and unitarity. We show that, in a very good approximation, the dynamic quantities reduce to functions of eight variables -- those of the Boltzmann equation, supplemented by the energy of the hadron. Our method appears capable of deducing the properties of hot dense nuclear matter from data already measured in experiments on the collisions of heavy nuclei.

1. Abstract of paper: *Phys. Rev. C* **40**, 2641 (1989).
2. Oregon State University, Corvallis.
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4. Northwestern State University, Natchitoches, LA 71457.
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DISPERSION RELATIONS FOR CAUSAL GREEN'S FUNCTIONS: DERIVATIONS USING THE POINCARÉ-BERTRAND THEOREM AND ITS GENERALIZATIONS¹

K.T.R. Davies, R. W. Davies², G. D. White³

A famous theorem by Poincaré and Bertrand formally describes how to interchange the order of integration in a double integral involving two principal-value factors. This theorem has important applications in many-body physics, particularly in the evaluation of response functions (or "loop integrals") at either zero or finite temperatures. Of special interest is the loop containing an integration with respect to the energy of two causal propagators. It is shown that such a response function with two boson or two fermion lines behaves statistically like a boson, while the response function containing a boson and a fermion behaves like a fermion. Examples are given of typical loop integrals occurring in the solution of Dyson's equations for nuclear matter in the presence of delta, nucleon, and pion interactions. A "form factor" that is essential for the convergence of the nucleon-pion loop integral is chosen to have little effect on the analogous nucleon-delta loop integral. The Poincaré-Bertrand (PB) theorem is then generalized to multiple integrals and higher-order poles. From the generalization of the theorem to triple integrals, it is shown that causality is rigorously maintained, at zero temperature, for convolutions with respect to the time of products of Green's functions and thus for Dyson's equations. Also, for finite temperature, the three-propagator loop integral satisfies the statistics appropriate for the loop as a whole, in direct analogy with the result for the two-propagator loop. The intimate connection between the PB theorem and analyticity (or causality) is clearly demonstrated. Although this work considers explicitly only nuclear physics examples, the results are relevant to other fields where many-body theory is used.

1. Abstract of paper: *J. Math. Phys.* **31**, 1356 (1990).
2. GTE Laboratories, Inc., Waltham, MA 02254.
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EVALUATION OF THE REAL PARTS OF FERMION AND BOSON PROPAGATORS USING DISPERSION RELATIONS

K.T.R. Davies, G. D. White¹, R. W. Davies²

Considerable theoretical and technical progress has been made in our studies of nucleon-delta-pion interactions.³ The immediate aim of this program is to solve self-consistently Dyson's equations at zero temperature in nuclear matter. Of particular interest here is the calculation of the real and imaginary parts of the delta-particle and pion Green functions.

In the computational part of this program, one of the most difficult problems has been the evaluation of various kinds of principal-value (PV) integrals. These integrals arise naturally in the theory because the real and imaginary parts of a Green function are formally related through a Hilbert transform, thereby guaranteeing that causality is rigorously satisfied. However, such a dispersion relation is more than just a mathematical artifact. For at least two reasons, it is straightforward and probably necessary to evaluate the real part of a propagator *numerically* (from its imaginary part) by using a Hilbert transform. First of all, in intermediate-energy physics it is usually much easier to evaluate directly the imaginary part of a Green function than its real part. The second, more compelling reason is that in solving Dyson's equations, approximations are often introduced which implicitly destroy causality. We have taken the point of view that the imaginary part of a Green function is calculated directly from Dyson's equations, but its real part is obtained from a dispersion relation, so that exact causality is always maintained.³ This philosophy also applies to auxiliary functions which comprise only part of the propagator, e.g. its self-energy and its width. In fact, if the self-energy and width have been determined by the above prescription, these may be combined to form the total propagator which then automatically satisfies causality.⁴

The dispersion relations involving such propagators (or their self-energies and widths) can be complicated, especially at finite temperatures.⁴ However, even in the zero temperature limit the resulting PV integrals contain nontrivial step functions. Moreover, at zero temperature the propagators themselves contain additional step functions. Such step functions must be carefully

taken into account in order to accurately evaluate the PV integrals. Also, it is crucial to pick a numerical discretization which gives optimum convergence of the integrals. The evaluation of these integrals involves some analytic manipulation, but the choice of meshes strongly reflects the limitations imposed by the physics of the problem.

We mention too that we require very high accuracy at all levels of our computations, mainly because of potential errors introduced due to sharp resonances occurring in the Green functions. Examples of such resonances occur for the pion propagator which we have shown to have two distinct families of "spikes." Finally, we have derived several general expressions for numerically calculating the real parts of fermion and boson propagators, and these have been extensively tested using the delta and pion propagators arising in our nuclear matter studies. Several papers describing these results are in preparation.

1. Northwestern State University, Natchitoches, LA 71457.

2. GTE Laboratories, Inc., Waltham, MA 02254.

3. See "Relativistic Transport Theory of Fluctuating Fields for Hadrons," this report.

4. See "Dispersion Relations for Causal Green's Functions: Derivations Using the Poincaré-Bertrand Theorem and Its Generalizations," this report.

TREATMENT OF THE SHARP SPIKES IN THE PION GREEN'S FUNCTION

K.T.R. Davies and G. D. White¹

In our nuclear matter studies, in which the effects of nucleon-pion-delta interactions are included,^{2,3} we find that the pion Green's function is expressed as

$$D(p, \omega) = D_0(p, \omega) / [1 - D_0(p, \omega) \pi(p, \omega)], \quad (1)$$

where $p = |\vec{p}|$ represents the momentum and ω , the energy. The function $D_0(p, \omega)$ is the "bare" pion propagator

$$D_0(p) = (\omega^2 - p^2 - m_\pi^2 + i\epsilon)^{-1}, \quad (2)$$

and ϵ is infinitesimal. The function $\pi(p, \omega)$ arises from a "loop integral" involving the nucleon and delta propagators,^{2,4} and it is easily shown from Eqs. (1) and (2) that its real and imaginary parts contribute to the self-energy and width, respectively, of the pion.

In the absence of nucleon-delta-pion interactions, $\pi(p, \omega)$ vanishes and the poles of $D(p, \omega)$ occur at $\omega^2 = p^2 + m_\pi^2$, with

$$D(p, \omega) \rightarrow D_0(p, \omega) = \frac{\mathcal{P}}{(\omega^2 - p^2 - m_\pi^2)} \quad (3)$$

$$- \pi i \delta(\omega^2 - p^2 - m_\pi^2),$$

where $\mathcal{P}$ indicates the principal-value of the integral. From Eq. (3) we see that in this limit the imaginary part of the pion propagator is a delta function. However, even when there are interactions present, the $\text{Im}[D(p, \omega)]$ contains a delta function for those ω values for which the $\text{Im}[\pi(p, \omega)]$ vanishes. This occurs at normal nuclear matter density for

$$\omega \leq \omega_0 = 154.0 \text{ MeV.}^3$$

For $\omega > \omega_0$ the $\text{Im}[D(\omega, p)]$ is no longer a delta function but it still contains a very sharp "spike" which becomes more and more like a delta function as $\omega \rightarrow \omega_0 +$.

Such sharp spikes cannot be easily treated using the usual numerical meshes in ω and p . For example, it is computationally prohibitive to make the mesh spacing in p much smaller than $\Delta p_0 = 0.1 \text{ fm}^{-1}$, while the spikes for ω values just above ω_0 have widths considerably smaller than Δp_0 . Thus, it becomes of interest to determine the spikes using a special parametrization.

We have adopted the following method. For a given value of ω , we parametrize the Padé form using

$$\mathcal{D}_R(\omega, p) = [1 + \rho(\omega)p][\lambda(\omega) + \kappa(\omega)p]^{-1}, \quad (4)$$

where ρ , λ , and κ are all complex numbers. For p values in the neighborhood of the spike, we fit *both* the *real* and *imaginary* parts of $D(\omega, p)$ to $\mathcal{D}_R(\omega, p)$. Note that this is a six-point fit, involving three distinct p values. Then, from Eq. (4) it is clear that in the resonance region

$$\text{Im}[D(\omega, p)] = g_R(\omega, p) = \frac{A(\omega) + B(\omega)p + C(\omega)p^2}{\alpha(\omega) + \beta(\omega)p + p^2}, \quad (5)$$

where A , B , C , α , and β are real numbers which can be expressed in terms of the real and imaginary parts of ρ , λ , and κ . Also, we find that

$$\beta^2 - 4\alpha < 0, \quad (6)$$

which means that $g_R(\omega, p)$ has poles only at complex values of p , a feature which is essential both for the physics and for the computational work. In other parametrizations which were considered, unwanted real poles sometimes occurred, especially for ω values close to ω_0 . It should be emphasized too that our focus is on $\text{Im}[D(\omega, p)]$, which is the function one needs for the explicit evaluation of the pion-nucleon loop integral.²⁻⁴ However, a useful byproduct of the fit to Eq. (4) is that we also determine the $\text{Re}[D(\omega, p)]$ in the resonance region.

1. Northwestern State University, Natchitoches, LA 71457.

2. See "Relativistic Transport Theory of Fluctuating Fields for Hadrons," this report.

3. See "Evaluation of the Real Parts of Fermion and Boson Propagators Using Dispersion Relations," this report.

4. See "Dispersion Relations for Causal Green's Functions: Derivations Using the Poincaré-Bertrand Theorem and Its Generalizations," this report.

STUDIES OF FINITE-LIMIT PRINCIPAL-VALUE INTEGRALS IN NUCLEAR AND CONDENSED MATTER PHYSICS

K.T.R. Davies, M. L. Glasser¹, R. W. Davies²

The physics literature is replete with examples where the principal-value (PV) of an integral must be evaluated. The PV, of course, is used extensively in the general theory of Green's functions, particularly for those propagators which represent elementary particles. Furthermore, studies in both nuclear physics³⁻⁵ and in condensed matter physics⁶ clearly show that the theory of Green's functions is very

useful in describing properties of true many-body systems.

In recent years, in intermediate-energy nuclear physics, there has been a resurgence of interest in the theory of propagators, mainly because of various attempts to solve, microscopically, problems involving the interactions among nucleons, delta-particles, pions, and higher-mass mesons.³⁻⁵ In these studies, much attention is directed to the evaluation of various "loop integrals" (or response functions) which contain the product of two causal Green's functions integrated over an energy or frequency. However, in analyzing the relation between the real and imaginary parts of these loop integrals, one encounters *double* integrals involving two PV factors.^{3,4} Then, in such double integrals, if one reverses the order of integration, it is especially convenient to resurrect a theorem due to Poincaré and Bertrand.⁴ Applying this theorem, one can properly relate the real and imaginary parts of the loop integrals by a dispersion relation, thereby guaranteeing that causality is rigorously obeyed.^{3,4}

Moreover, parallel to all of these theoretical developments over the years have been the accompanying studies involving numerical evaluation of various PV integrals.⁵ Also, in many papers the PV definition has been extended to higher-order poles.⁷ We mention too that most of this work has emphasized the evaluation of PV integrals containing *infinite-limit* integrals. However, because of the occurrence of various step functions which arise, particularly for zero-temperature Green's functions in nuclear matter,⁵ it is clear that one easily finds cases in which infinite PV integrals become truncated. Finite-limit PV integrals also occur in condensed-matter physics.⁶

Thus, because of the applicability to a wide variety of problems,³⁻⁶ we have begun a general study of the theoretical and computational evaluation of *finite-limit* PV integrals. For single integrals, the most important result is the following. Assume that there exists a "quadrature relation,"

$$\frac{dG(x)}{dx} = F(x), \quad (1)$$

where

$$G(x) = g(x)/x^n; \quad n \geq 1 \quad (2)$$

and $g(x)$ is well behaved over the range $-A \leq x \leq B$; $A, B > 0$. Then, it can be shown that

$$\mathcal{P} \int_a^b G(x) dx = F(b) - F(-a), \quad (3)$$

where $0 < a \leq A$, $0 < b \leq B$, and $\mathcal{P}$ denotes the PV of the integral. Equation (3) requires special justification for higher-order poles (i.e. $n \geq 2$). In addition, quadrature relations are being studied for *double* finite-limit PV integrals to which the Poincaré-Bertrand theorem⁴ applies.

1. Clarkson University, Potsdam, NY.

2. GTE Laboratories, Inc., Waltham, MA.

3. See "Relativistic Transport Theory of Fluctuating Fields for Hadrons," this report.

4. See "Dispersion Relations for Causal Green's Functions: Derivations Using the Poincaré-Bertrand Theorem and Its Generalizations," this report.

5. See "Evaluation of the Real Parts of Fermion and Boson Propagators Using Dispersion Relations," this report.

6. D.J.W. Geldhart and R. Taylor, *Can. J. Phys.* 48, 155 (1970).

7. K.T.R. Davies and R. W. Davies, *Can. J. Phys.* 67, 759 (1989)

COMMENT ON "SIMULTANEOUS ANALYSES OF ELASTIC SCATTERING AND FUSION CROSS SECTIONS FOR THE $^{32}\text{S} + ^{58,64}\text{Ni}$ SYSTEMS AT ENERGIES NEAR THE COULOMB BARRIER"

G. R. Satchler, M. A. Nagarajan², J. S. Lilley²,
I. J. Thompson³

An explanation is offered for the large fusion radii obtained in the optical model description of heavy-ion fusion given by Udagawa et al. An extension of the model is suggested, and possible effects on the spin distribution are discussed. It is contended that the large fusion radii *cannot* be deduced from the elastic scattering alone. The role of Coulomb excitation for these systems is also discussed.

1. Abstract of paper: *Phys. Rev. C* 41, 1869 (1990).

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TRANSFER REACTIONS AND OPTICAL POTENTIAL AMBIGUITIES FOR LIGHT HEAVY-ION SYSTEMS¹

G. R. Satchler

We investigate the extent to which measurements of transfer reactions between light heavy ions might provide a signature of a partial transparency in their mutual optical potential. This transparency allows some contribution from impact parameters smaller than the grazing one. The $^{12}\text{C}(^{12}\text{C},^{13}\text{C})^{11}\text{C}$ ground-state transition is used as an example. Optical potentials are derived from $^{12}\text{C} + ^{12}\text{C}$ elastic scattering at energies from $E/A = 20$ to 85 MeV and used in DWBA calculations of the transfer. At the lower energies, potentials which provide similar elastic scattering at forward angles also predict very similar peak cross sections for transfer, but the angular distribution away from this main peak depends upon the degree of absorption present. The sensitivity increases as the energy is raised, so that at $E/A = 85$ MeV even the peak cross section becomes very dependent upon the optical potential used.

1. Abstract of paper: *Nucl. Phys. A* 505, 103 (1989)

SCATTERING OF 344.5-MeV ^{12}C IONS ON ^{11}B , ^{12}C , ^{27}Al , ^{58}Ni , ^{90}Zr , and ^{197}Au NUCLEI¹

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A survey of the elastic scattering of ^{12}C ions at 344.5 MeV has been made by measuring angular distributions for targets of ^{11}B , ^{12}C , ^{27}Al , ^{58}Ni , ^{90}Zr , and ^{197}Au nuclei. The data were analyzed using

two versions of the optical model: (a) a potential with Woods-Saxon form for both the real and imaginary part, (b) a folded potential for the real part based on the density- and energy-dependent DDM3Y interaction, supplemented by an imaginary potential of Woods-Saxon form. Except for ^{27}Al , the elastic data are consistent with the scattering from the folded potential without any need for renormalization. Data were also obtained for $^{12}\text{C} + ^{12}\text{C}$ exciting the 4.44-MeV 2_1^+ state. Coupled-channels analysis implied a potential deformation length of -1.15 fm for this transition.

1. Abstract of paper to be published in *Nuclear Physics A*.

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OPTICAL POTENTIAL AMBIGUITIES AND $^{16}\text{O} + ^{16}\text{O}$ AT 350 MeV¹

M. E. Brundan² and G. R. Satchler

The elastic scattering of $^{16}\text{O} + ^{16}\text{O}$ at 350 MeV has been reanalyzed using more general optical model potential shapes in an attempt to resolve the ambiguity over the order of rainbow seen in the angular distribution. We conclude that probably it is the primary rainbow, determining the real potential to have a volume integral $J_V = 295 \pm 5$ MeV fm³. However, the use of real potentials with non-monotonic shapes defined by splines does still allow the possibility of it being the secondary rainbow generated by a deeper potential. In addition, the use of splines introduces a more shallow potential which also implies observation of the primary rainbow.

1. Abstract of paper to be published in *Physics Letters B*.

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THE "DISTRIBUTION OF BARRIERS" INTERPRETATION OF HEAVY-ION FUSION¹

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Heavy-ion fusion cross sections obtained from a distribution of potential barriers are discussed. The smoothing due to quantal barrier penetration is shown to replace a set of discrete barriers by an effective continuous distribution. It is shown how this smoothed distribution may be obtained rather directly from the measured cross sections at near- and sub-barrier energies.

1. Abstract of paper to be published in *Physics Letters B*.

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EXPLORATORY STUDIES OF THE ELASTIC SCATTERING OF $^{11}\text{Li} + ^{12}\text{C}$ ¹

G. R. Satchler, K. W. McVoy², M. S. Hussein³

Calculations have been made of the elastic scattering of $^{11}\text{Li} + ^{12}\text{C}$ at $E/A = 30$ and 85 MeV as an example of the scattering to be expected for "exotic" neutron-rich light nuclei. The real optical potential was generated from a folding model using Hartree-Fock densities for ^{11}Li . A variety of assumptions for the absorptive imaginary potential were explored, subject to the important constraint that the predicted reaction cross section remain reasonable. Contrary to some expectations, we provide evidence that these weakly bound systems do not exhibit the diffractive type of scattering that is characteristic of strong absorption. If anything, their more diffuse real potentials can result in an enhancement of the refractive features.

1. Abstract of paper to be published in *Nuclear Physics A*.

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HEAVY-ION SCATTERING AND REACTIONS NEAR THE COULOMB BARRIER AND "THRESHOLD ANOMALIES"¹

G. R. Satchler

The couplings between the various reaction channels available for the collision of two heavy ions become especially important at energies near the top of their mutual Coulomb barrier. In particular, they result in a "threshold anomaly" in the dependence on energy of the optical model potential that describes their elastic scattering and a strong enhancement of their fusion cross sections in this energy region. The evidence for these "anomalies" is reviewed and their theoretical explanation is discussed. A dispersion relation between the real and imaginary parts of the optical model potential is described and its use is illustrated. Finally, an extension of the one-channel optical model that allows for simultaneous analysis of fusion and elastic scattering is presented and its applications considered.

1. Abstract of paper to be published in *Physics Reports*.

ELASTIC AND INELASTIC SCATTERING OF ^{16}O BY ^{92}Zr AT ENERGIES NEAR THE COULOMB BARRIER¹

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Angular distributions for the elastic and inelastic scattering of ^{16}O by ^{92}Zr were measured at 56 MeV bombarding energy, as well as excitation functions at $\theta_{\text{c.m.}} = 174.7^\circ$ from 34 to 54 MeV in order to study the Coulomb-nuclear interference in the excitation of the 2_1^+ , 2_2^+ , and 3_1 states of ^{92}Zr . Data were also obtained for the $(^{16}\text{O}, ^{15}\text{N})$ ground-state proton transfer. The elastic and inelastic results were analyzed using coupled-channels calculations. None of the inelastic data could be fitted satisfactorily using the standard collective model. The interference pattern in the angular distribution for the 2_1^+ excitation could be reproduced by introducing a strong nuclear reorientation coupling for this state, accompanied by a

transition coupling much stronger than expected from the $B(E2)$ for this excitation. The best fit to the 3_1^- results was also obtained with a large reorientation term. The 2_2^+ data could be matched by using a more diffuse transition potential. The transfer angular distribution was reproduced very well in the DWBA. The overall behavior of the measured excitation functions indicates that one or more of the interaction parameters in the model must vary with the bombarding energy in order to accommodate the 2_1^+ interference minimum seen near 47 MeV. We deduce values of $B(E2)^\uparrow$ of about 0.09 and 0.04 e^2b^2 for excitation of the 2_1^+ and 2_2^+ states respectively, and $B(E3)^\uparrow = 0.11 e^2b^3$ for the 3_1^- state.

1. Abstract of paper: *Nucl. Phys. A* 514, 120 (1990).

DESCRIPTION OF PION SCATTERING FROM NUCLEI

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The coupled-channels program CUPID, designed for the description of pion elastic, inelastic, and charge exchange scattering, is being used to analyze measurements on these reactions, especially at energies in the vicinity of the (3,3) resonance. CUPID allows one to use momentum-dependent pion-nucleon interactions, including second-order corrections, based upon multiple scattering theory together with some semi-empirical adjustments. Microscopically-derived neutron and proton densities and transition densities may be used.

Of particular interest is the energy-dependence and the significance of the second-order corrections to the interaction, as well as the importance of channel coupling effects. The relative role of true absorption and of quasielastic contributions to the reaction cross sections is being studied.

The momentum dependence implies that the optical potentials are nonlocal; the characteristics of equivalent local potentials are being investigated.

The data analysis is directed toward the reliable extraction of nuclear structure information, especially the understanding of the relative importance of the neutron and proton contributions to the scattering.

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COMPARISON OF THE INELASTIC SCATTERING FROM NUCLEI OF VARIOUS HADRONS USING CONSISTENT TRANSITION INTERACTIONS

G. R. Satchler, D. J. Horen, R. L. Varner

Nuclear structure information derived from the analysis of the inelastic scattering of different hadrons is often difficult to compare because of the models used for the scattering interaction. Frequently a deformed optical potential is used, and there is ambiguity in relating this to the underlying transition densities. Of particular interest is the relative importance of neutron and proton contributions to an excitation, such as embodied in the M_n/M_p ratio.¹ For example, recent results from π^+/π^- scattering appear to be incompatible with analyses of the excitation by other hadrons such as heavy ions.²

We are attempting a more consistent approach by using a folding model to relate transition potentials to transition densities. Two kinds of ingredients are required:³ (i) neutron and proton transition densities, and (ii) an effective interaction between the projectile and each target nucleon. Transition densities are being generated by the use of either macroscopic models (e.g., Tassie) or microscopic RPA calculations, and the various approaches compared. The effective interaction for pions is obtained from multiple scattering theory, and for composite projectiles is being determined semi-phenomenologically by analysis of elastic scattering data.³

1. G. R. Satchler, *Nucl. Phys. A* 491, 413 (1989).

2. D. J. Horen, J. R. Beene, and F. E. Bertrand, *Phys. Rev. C* 37, 888 (1988); J. R. Beene et al., *Phys. Rev. C* 41, 920 (1990); D. J. Horen et al., this report.

3. G. R. Satchler, *Nucl. Phys. A* 472, 215 (1987).

SPIN-ORBIT FORCE IN TIME-DEPENDENT HARTREE-FOCK CALCULATIONS OF HEAVY-ION COLLISIONS¹

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K.T.R. Davies, S.-J. Lee⁴

We discuss the time-dependent Hartree-Fock equations which maintain independent nucleon spin degrees of freedom, and which include spin-orbit interactions. The complex numerical task of including the spin-orbit force in reaction studies is described in detail.

1. Abstract of paper: *Phys. Rev. C* **40**, 706 (1989).

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CLASSICAL PERIODIC TRAJECTORIES, WITH NEW APPLICATIONS TO TDHF THEORY AND BEAM DYNAMICS STABILITY

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M. J. Rhoades-Brown², M. R. Strayer, A. S. Umar³

Recently some very important studies in classical nonlinear dynamics have been completed.⁴⁻⁶ In this work, periodic motion in two-dimensional nonintegrable systems has been carefully analyzed. The most important results can be summarized as follows:

(1) A new algorithm has been developed for calculating the classical periodic trajectories.⁶ It is called the Monodromy method,⁴⁻⁶ and it is superior to the more conventional method of Poincaré sections for several reasons. First, it can be used to map out thoroughly the entire phase space, and it enables one to calculate unstable periodic trajectories as easily as the stable ones. Also, starting with a given periodic trajectory, one can very easily find another trajectory in the same family or in a new family which bifurcates off of the original family.

(2) A wealth of numerical data has been obtained, giving a rich variety of librational and rotational

motion.^{4,5} (About 5000 trajectories comprising roughly 50 families have been studied.)

(3) It has been especially convenient to present the data in the form of energy vs. period (E- τ) plots.^{4,5} These plots have very interesting topological properties which nicely reflect new features of the underlying dynamical motion.

(4) Very careful numerical and analytic studies have been made regarding the branching or bifurcation behavior of the families of periodic trajectories.^{4,5} This includes both isochronous branching (in which the period of the new family is the same as that of the parent family) and period-multiplying bifurcations (in which the period of the new family is a multiple of the period of the parent).

(5) The stability of the periodic trajectories determines the behavior of the phase space in which they are imbedded.⁴ Stable trajectories lie in regular regions of phase space, while unstable trajectories lie in chaotic regions.

This work has great promise of being extended to other problems, e.g. TDHF theory in nuclear physics. To understand the connection between the classical studies and TDHF, it is instructive to consider how one initiates the classical calculations when no periodic solutions are known. The logical way of beginning is to find first the families of small oscillations about the equilibrium points of the potential. When at least one trajectory from each of these families is known, one can use the Monodromy methods to go to larger amplitudes for each family and, in addition, to find many new families. The analogue in TDHF would be to start with the RPA solutions and use generalized Monodromy methods to generate solutions of large amplitude collective motion. Thus, small and large amplitude collective motion will be mapped out in TDHF just as it was in the classical case. Such a study will be very useful in nuclear structure and eventually in heavy-ion reactions.

Finally, the eigenvalues of the Monodromy matrix uniquely determines the *stability* of its phase space.⁴⁻⁶ Thus, we feel that the method should be especially useful for studying stability properties of the beam dynamics of various new accelerators, e.g., RHIC and the SSC.

Collaborations involving both TDHF and RHIC have already been initiated.

1. M.I.T., Cambridge, MA.
2. Brookhaven National Laboratory, Upton, NY.
3. Vanderbilt University, Nashville, TN.
4. M. Baranger and K.T.R. Davies, *Ann. Phys.* (N.Y.) 177, 330 (1987).
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ADDITIONAL STUDIES OF THE HÉNON-HEILES HAMILTONIAN

T. Huston¹, K.T.R. Davies, M. Baranger²

We have continued our studies of classical periodic trajectories in the famous two-dimensional Hénon-Heiles potential³

$$V(x, y) = \frac{1}{2} \left(x^2 + y^2 + 2x^2y - \frac{2}{3}y^3 \right). \quad (1)$$

which is invariant under $x \rightarrow -x$ and under rotations of 120° . The method used to calculate families of trajectories involves the Monodromy matrix formalism.⁴⁻⁶

In Fig. 7.1 we present an energy vs. period plot of the most important low-energy families. Because of the symmetries, there are *three* families which originate as small oscillations about the minimum of the potential. First, there are two librations, namely the usual horizontal (H) and vertical (V) families corresponding to straight lines (as $E \rightarrow 0$) in the x and y directions, respectively. However, due to the triangular symmetry, there is a totally *new* family T, a rotation, which is plotted in Fig. 7.2. This is the first time we have encountered a rotational family in the small oscillations limit.

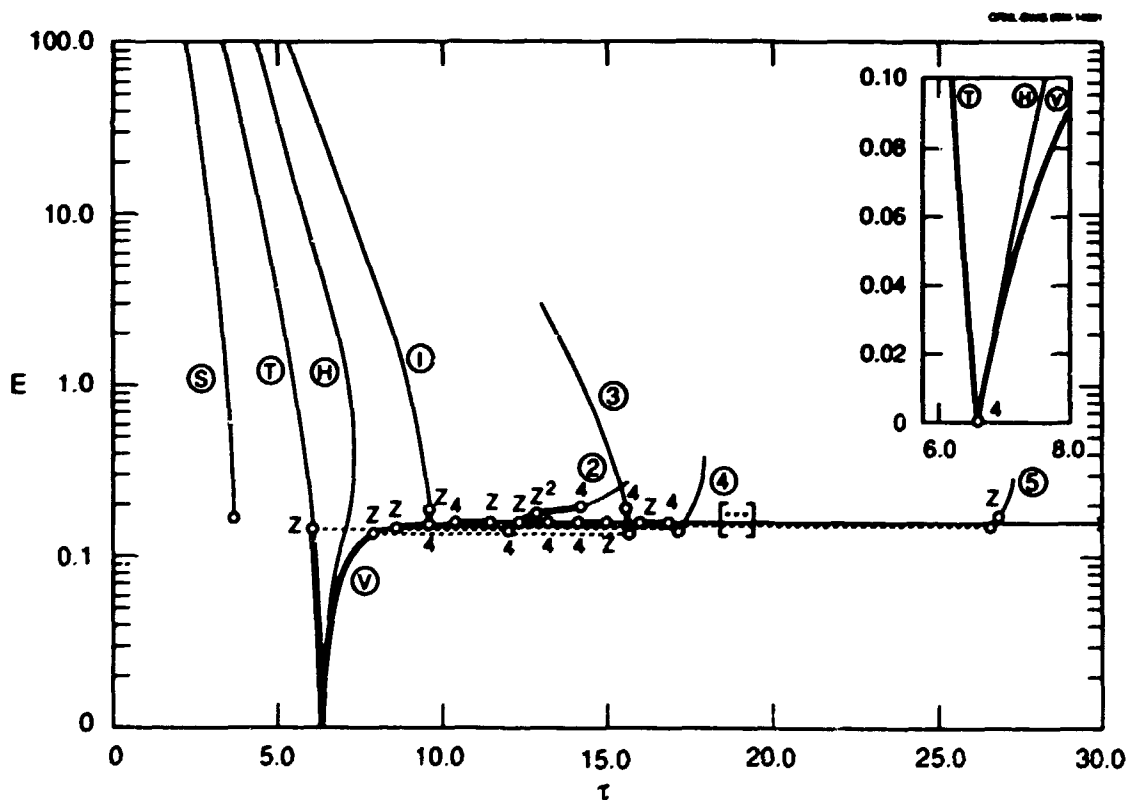


Fig. 7.1. Energy (E) vs. period (τ) plot of the most prominent low-energy families of the Hénon-Heiles potential. The circled letters V, H, T, and S refer to the vertical, horizontal, triangular, and saddle-point families, respectively, while the circled numbers 1, 2, 3, 4, and 5 label various branchings from V and T. The extra dark lines indicate stable trajectories.

Also, all three families have the same period at small oscillations, but unlike previous calculations^{4,5} there is no family whose period remains constant as the energy is increased. Another interesting feature is that for small energies, V and T are stable, while H is unstable. In Fig. 7.1, note that, as $\tau \rightarrow \infty$, the vertical family approaches an asymptotic limit which is equal to the energy of the saddle point. We see too that there is a "saddle-point" family (S) which originates from the saddle point of Eq. (1), a feature which has previously been observed for one other potential.⁵

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3. M. Hénon, p. 107 in *Chaotic Behavior of Deterministic Systems - Les Houches 1981* (North-Holland, Amsterdam, 1983).

4. M. Baranger and K.T.R. Davies, *Ann. Phys. (N.Y.)* 177, 330 (1987).

5. M.A.M. de Aguiar, C. P. Malta, M. Baranger, and K.T.R. Davies, *Ann. Phys. (N.Y.)* 180, 167 (1987).

6. M. Baranger, K.T.R. Davies, and J. H. Mahoney, *Ann. Phys. (N.Y.)* 186, 95 (1988).

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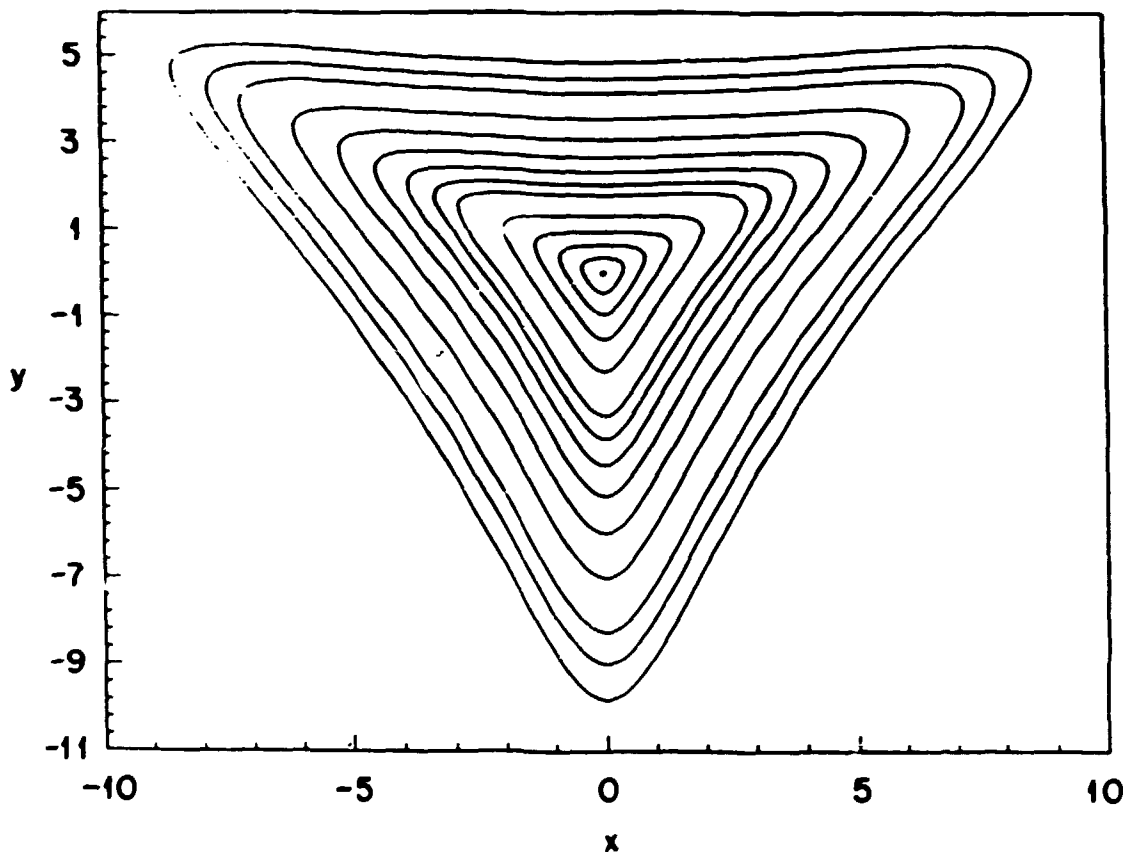


Fig. 7.2. x - y plot of many members of the rotational family, T. For small energies this trajectory is circular, while at higher energies, it becomes triangular in shape; hence, the name T.

HIGH-SPIN STRUCTURE IN ^{202}Pb

J. B. McGroarty

Lead-208 is perhaps the best closed-shell nucleus. For the lead isotopes near $A = 190$, there is strong evidence for the existence of collective rotational behavior in the spectra of Yrast levels. It is unclear where the transition from the spherical to deformed occurs. Fant et al.¹ have reported an extensive experimental investigation of the Yrast spectra of $^{200,202}\text{Pb}$, the goal of which is to shed further light on this question. They made a number of arguments based on the assumption of simple configurations for excited states in these nuclei, similar in spirit to work done by Blomqvist and co-workers.² We have performed an almost complete shell model calculation

of the structure of ^{202}Pb in order to provide a more definitive spherical model picture of the structure of this nucleus. The work is a natural extension of earlier studies³ of the Pb isotopes. Six neutron hole orbits are included in the model space - the $3p_{1/2}$, $3p_{3/2}$, $2f_{5/2}$, $2f_{7/2}$, $1h_{9/2}$, and the $1i_{13/2}$. All Pauli-allowed distributions of six holes in the six orbits are included, with the exception that no more than four holes in the $1i_{13/2}$ orbit are allowed. The resulting matrices are large - on the order of $20,000 \times 20,000$, making this the largest calculation done with the Oak Ridge-Rochester code. The interaction is essentially identical to one found by Blomqvist. We use the same set of single-hole energies used previously. The resulting calculated spectra for $^{206,204,202}\text{Pb}$ are shown in Fig. 7.3, where they are compared with

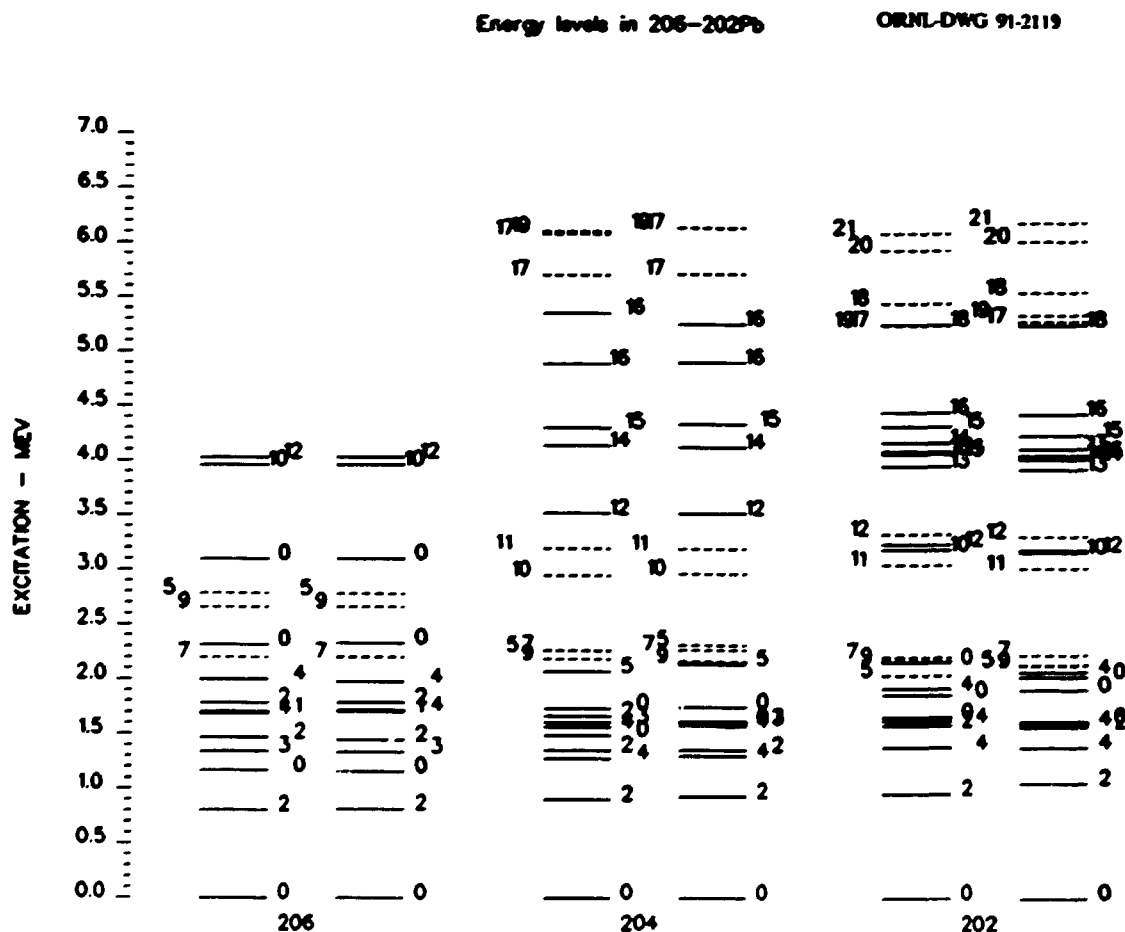


Fig. 7.3. Energy levels in $^{206,204,202}\text{Pb}$. In each spectra experimental levels are to the left. Positive parity levels are indicated with solid lines and spin values to the right. Negative parity levels are indicated with dashed lines and with spin values to the left.

experiment. We include all levels included by Fant et al. in their discussion, and we include the lowest calculated levels for each spin in the calculated spectra - i.e., if Fant et al. list three $J=4$ states, we include the lowest three calculated $J=4$ states. The agreement between theory and experiment is extremely good for all three isotopes shown. The systematic features of the spectra of Yrast levels are almost exactly reproduced in the calculations. There is no evidence in the spectra shown here of the onset of collective deformation in ^{202}Pb . Calculations of the $J=0^+$ spectra for ^{200}Pb and for electromagnetic observables in ^{202}Pb are in progress.

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PERTURBATION THEORY FOR STRONGLY INTERACTING ATOMIC SYSTEMS¹

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The strong-potential Born approximation has been formulated to include effects of elastic scattering in initial and final states. We use the standard distorted-wave theory and the eikonal approximation to derive closed-form expressions for scattering-wave functions. Our results show that lowest-order theories must account for off-energy-shell electron propagation in the strong potential as well as for elastic scattering in initial and final states. Capture from inner shells and radiative electron capture are computed to illustrate the theory.

1. Abstract of paper: *Phys. Rev. A* **41**, 207 (1990).
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TWO-BODY FRAGMENTATION CHANNELS OF THREE-BODY SYSTEMS¹

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An asymptotic expansion of the wave functions for the fragmentation channels of three-body systems is developed in hyperspherical coordinates. It is shown that, to any finite power in $1/R$, where $mR^2 = \sum_i m_i r_i^2$ is the trace of the inertia tensor, the expanded wave function is an analytic finite sum of Sturmian functions. The expansion is carried out explicitly through order $1/R^4$. These asymptotic states converge (as $R \rightarrow \infty$) to polarized orbitals for two-electron systems, and also provide improved dissociation channels for molecular ions, such as HD^+ . Asymptotic potential curves for He and μ^- -H systems are presented as illustrations.

1. Abstract of paper: *Phys. Rev. A* **41**, 1225 (1990).
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POST-COLLISIONAL STARK MIXING IN AUGER PROCESSES¹

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Post-collisional effects on the electronic distribution of autoionization processes are studied. A formulation, including both the long range of the projectile Coulomb potential and the polarization potential is presented. The latter potential mixes close lying levels of autoionizing states with equal magnetic quantum number, giving rise to a significant perturbation of the angular and energy distribution of the electron spectra. Particular attention is paid to the mixing of autoionizing levels of helium $2s2p^1P$ and $2p^2^1D$. Deviation from 90° symmetry is studied, and comparison with experiments is presented.

1. Abstract of paper: *Phys. Rev. A* **42**, 3971 (1990).
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ANGULAR CORRELATION OF AN AUGER ELECTRON WITH A PHOTOELECTRON IN THE DIRECTION OF LINEAR POLARIZATION¹

L. Végh² and R. L. Becker

It is shown that if the photoelectron is detected along the direction of linear polarization, the intermediate ion is aligned along that direction. The angular correlation of a subsequent Auger electron is given, therefore, by

$$W_c(\theta) \propto 1 + \sum_{k=2,4,\dots} \alpha_k A_{k0}^c P_k(\cos\theta)$$

where the A_{k0}^c describe the alignment and the α_k the Auger decay. Krause and Caldwell³ have measured

this correlation for the $6p^2(^3P_0) \rightarrow 5d_{5/2} 5s_{1/2}$ Auger transition in Pb. The photoelectron may have orbital angular momentum $\ell = 1$ or 3; the maximum value of k is 4. We have calculated the α_k from a Racah-algebraic expression in the literature, and the A_{k0}^c by assuming a dipole transition with the Z-axis chosen along the polarization. We found the ratio

$$W_c(180^\circ)/W_c(90^\circ) = 4 \text{ for pure } \ell=1 \text{ and } 1\frac{113}{114} \text{ for}$$

pure $\ell=3$. The experimental result³ is $3.8^{+0.6}_{-0.4}$.

1. Abstract of paper presented at X-90 (15th Intern. Conf. on X-Ray and Inner-Shell Processes) July 1990, slightly updated.

2. Guest Assignee from Institute of Nuclear Research, Debrecen, Hungary.

3. M. Krause and D. Caldwell, to be published.

REFLECTION SYMMETRY AND ANGULAR CORRELATIONS OF AUTOIONIZATION ELECTRONS¹

R. L. Becker, L. Végh², J. H. Macek³

The theory of angular correlations of electrons from autoionizing states relates the source parameters called state multipoles, ρ_{KQ} , to observed angular

distributions of electrons detected in coincidence with scattered projectiles or directly ejected electrons. This theory usually employs reflection symmetry in a plane, expressed in the form $\rho_{KQ} = (-1)^Q \rho_{K,-Q}$. This relation holds if the initial autoionizing state is either a pure state or a mixed state. We point out that when the excitation mechanism produces an atomic species in a pure state, then several additional nontrivial relations among the state multipoles hold.

The reflection symmetry in a plane specified by the incident and scattered projectile direction, which has been cited above, implies that the density matrix element $\rho_{MM'}(JJ')$ satisfies a relation involving the change of sign of both M and M' , namely

$$\rho_{MM'}(JJ') = (-1)^{J-M+P+J'-M'+P'} \rho_{-M,-M'}(JJ'), \quad (1)$$

where P and P' are the parities of the states with angular momenta J and J' , respectively. When reflection symmetry is applied to the transition amplitudes $\langle k', JM j_u m_u | T | k, j_i m_i \rangle$ where $j_u m_u$ refers to all unobserved fragments in the final state and $j_i m_i$ to the initial state, then one has the relation

$$\begin{aligned} & \langle k', JM j_u m_u | T | k, j_i m_i \rangle \\ &= (-1)^{J-M+P+j_u-m_u+P_u+j_i-m_i+P_i} \\ & \times \langle k', J-M j_u -m_u | T | k, j_i -m_i \rangle \end{aligned} \quad (2)$$

where P_u and P_i are the parities of the unobserved part of the final state and of the initial state, respectively. In some experimental situations, it is known that $m_u = m_i = 0$. Then $\rho_{MM'}(JJ')$ refers to a pure state for which the additional relation follows,

$$\rho_{MM'}(JJ') = (-1)^{J-M+P} (-1)^{j_u+P_u+j_i+P_i} \rho_{-M,-M'}(JJ'). \quad (3)$$

We show that Eq. (3) and the similar transposed equation imply relations between state multipoles of the form

$$\rho_{KQ} = \sum_{K'Q'} W(KQ, K'Q') \rho_{K'Q'}, \quad (4)$$

where $W(KQ, K'Q')$ is a geometrical factor. We have computed $W(KQ, K'Q')$ explicitly and have applied Eq. (4) to excitation of autoionizing states of He.

1. Abstract of paper presented at X-90 (15th Intern. Conf. on X-Ray and Inner-Shell Processes) July 1990.

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EXCHANGE EFFECT ON THE ANGULAR CORRELATION BETWEEN DIRECTLY IONIZED AND AUTOIONIZED ELECTRONS OF THE SAME ENERGY¹

L. Végh², R. L. Becker, J. H. Macek³

In both photoionization and electroionization the availability of incident beams of very sharp energy makes possible the study of nearly monoenergetic directly ejected electrons. One then can investigate the effect of electron exchange between the directly ionized electron and another electron of about the same energy. Many (e,2e) experiments have been done with both final electrons detected at the same energy and analyzed with a model containing as a factor an antisymmetrized free electron-electron cross section. Recently, Doering et al.⁴ have reported some results on the angular correlation between an Auger electron from Ar and a directly ejected electron of nearly the same energy. An interference term in the angular correlation, resulting from electron exchange, should occur here and also in photoionization-autoionization experiments in which the photoelectron has approximately the same energy as the autoionized electron.

To exhibit an exchange correlation in the simplest way, we consider the dipole photoionization of an s-electron, $n_1s \rightarrow E_1p$, followed by monopole autoionization from an s^2 shell, $(n_2s)^2 \rightarrow n_1sE_2s$. If the target, A, is initially in a $1S$ state, the final ion, A^{++} , is also in a $1S$ state. Energy conservation gives $E_1 + E_2 = \hbar\omega - E_{\text{exc}}(A^{++}) = \hbar\omega'$. At the center of the resonance $E_1 + E_2 \rightarrow 2E_R$ where E_R is the central autoionization energy. If the photon travels along the z-axis with linear polarization along the x-axis, the directly ionized electron has an amplitude proportional to $\hat{k}_1 = \sin\theta \cos\phi$. The autoionized electron is isotropic. Because the photoelectron and autoionized

electron are in a singlet state, the orbital state must be symmetric, so that the complete amplitude for the two-step process can be written

$$A_s(\bar{k}_1, \bar{k}_2; \hbar\omega) = \frac{1}{\sqrt{2}} \left[\frac{a(k_2, k_1; \hbar\omega) \sin\theta_2 \cos\phi_2}{E_1 - E_R + i\Gamma/2} + \frac{a(k_1, k_2; \hbar\omega) \sin\theta_1 \cos\phi_1}{E_2 - E_R + i\Gamma/2} \right], \quad (1)$$

where the function a is slowly varying. The cross section for detecting electrons in the directions $\hat{k}_A$ and $\hat{k}_B$ with $E_1 + E_2 = 2E_R$ is proportional to

$$\frac{\sin^2\theta_B \cos^2\phi_B}{(E_A - E_R)^2 + \left(\frac{\Gamma}{2}\right)^2} + \frac{\sin^2\theta_A \cos^2\phi_A}{(E_B - E_R)^2 + \left(\frac{\Gamma}{2}\right)^2} + \frac{2\text{Re} \sin\theta_A \cos\phi_A \sin\theta_B \cos\phi_B}{\left(E_A - E_R + \frac{i\Gamma}{2}\right) \left(E_B - E_R - \frac{i\Gamma}{2}\right)} \quad (2)$$

For fixed $E_A - E_B$ Eq. (3) has dependence on $\hbar\omega'$ similar to that of two interfering resonances as, e.g., in R-matrix theory. This is quite different from the Beutler-Fano profile for single ionization, which results from the interference between a resonant and a nonresonant amplitude.

1. Abstract of paper presented at X-90 (15th Int. Conf. on X-Ray and Inner-Shell Processes), July 1990.

2. Guest Assignee from Institute of Nuclear Research, Debrecen, Hungary.

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THE THEORY OF ELECTRON-ION COLLISIONS: THE ROLE OF DOUBLY EXCITED STATES¹

D. C. Griffin², M. S. Pindzola³, C. Bottcher

The important contributions of doubly excited autoionizing states to electron-impact excitation, ionization, and recombination are reviewed. Various theoretical methods of treating these states are considered, and theoretical cross sections are presented

and compared with experimental measurements where available.

1. Abstract of paper: pp. 274-301 in *Proceedings of the Summer School of Computational Atomic and Nuclear Physics, Sewanee, TN, 1989*, World Scientific Publishing Co., Singapore (1990).

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DYNAMICAL THRESHOLDS FOR THE EXISTENCE OF EXCITED ELECTRONIC STATES OF FAST IONS IN SOLIDS

Jörg Müller¹ and Joachim Burgdörfer²

One fundamental problem in the study of the formation and evolution of bound states of fast charged particles penetrating solids concerns the existence of excited states inside a solid. The interaction with the medium, the ionic cores of the target as well as the delocalized valence electrons, causes collisional destruction and broadening of all levels. Furthermore, the collective response of the medium, in particular of the quasi-free valence (or conduction) electrons, leads to dynamical screening of ionic potential of the projectile.

We have studied the bound state spectrum of a hydrogenic ion with charge Q in the presence of a dynamical screening potential.³⁻⁶ The conduction electrons are represented by an electron gas. The nonrelativistic Hamiltonian of an electron in the dynamical screening potential is given by

$$H = \frac{p^2}{2} + V_{\infty}(\rho, z) \quad (1)$$

where V_{∞} is the dynamical screening potential. Approximate energy eigenvalues of (1) can be found by expanding trial wave functions in a suitable basis. We have used a hydrogenic basis with basis size for given m of ≈ 600 . The expansion converts the Schrödinger equation into a matrix eigenvalue equation which can be solved by diagonalization.

Figure 7.4 displays the $m = 0$, $n = 2, 3, 4$, and 5 manifolds of He^+ in carbon as a function of the

inverse projectile velocity V_p^{-1} . In the weak perturbation limit ($V_p^{-1} \rightarrow 0$) each manifold displays a Stark splitting determined by the electric quantum number k . The Stark splitting of low-lying energy levels in the solid has been observed in resonant coherent excitation of the $n = 2$ manifold⁷ of highly charged ions.

We have applied this analysis to determine critical threshold velocities, v_c above which a given n manifold becomes bound. We find an $n = 3$ threshold in He^+ of $v_c = 3.6$ a.u. which is in amazing agreement with the recent experimental value⁸ of $v_c \approx 3.7$ a.u.

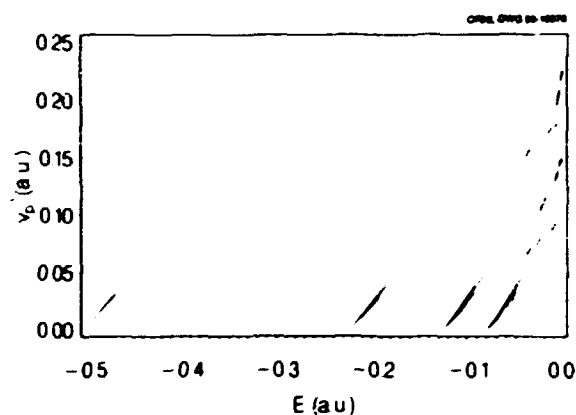


Fig. 7.4. Energy level diagram for the $m = 0$, $n = 2$ to $n = 5$ manifolds of He^+ in carbon ($\omega_p = 0.81$).

1. Partial support paid by Joint Institute for Heavy Ion Research.

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NUMERICAL STUDIES OF HIGH-TEMPERATURE SUPERCONDUCTOR MODELS

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W. Macready²

Although the mechanism of high-temperature superconductivity⁴ has not yet been established, the most likely mechanism appears at present to be the formation of hole pairs in the copper-oxygen planes which are common to these materials. A large antiferromagnetic interaction is observed between the d electrons on the Cu⁺⁺ sites, and this magnetic interaction may drive hole pairing. (For a review see Ref. 5). A widely studied model of these copper-oxygen planes is the t-J model,⁶⁻⁸ which is described by the Hamiltonian

$$H_J = -t \sum_{\langle i,j \rangle, \sigma} (c_{i\sigma}^\dagger c_{j\sigma} + \text{h.c.}) + J \sum_{\langle i,j \rangle} \left(\vec{S}_i \cdot \vec{S}_j - \frac{1}{4} n_i n_j \right) \quad (1)$$

The J term alone is essentially the Heisenberg antiferromagnet, which is an accurate model of many magnetic properties of the undoped materials. (We recently completed an extensive review article on this subject,⁹ which was an invited contribution to the Caltech Concurrent Computation Project.) Unfortunately, Monte Carlo studies of dynamical fermions are very difficult, so it has been possible to study this system only numerically using exact diagonalization (usually on a 4×4 lattice using the Lanczos algorithm) or using Monte Carlo methods in the static hole limit. We have carried out such numerical studies on local VAX machines (for Lanczos^{10,11}) and the ORNL Intel iPSC/860 (for the Monte Carlo work,¹¹ which used an algorithm we developed for Heisenberg model studies¹²). Although early Lanczos results appeared to confirm hole pair formation in this model, it is now believed that holes in this system preferably form arbitrarily large clusters rather than just pairs. A proposed solution to this "phase separation" problem is that the neglect of the long-range hole-hole-Coulomb repulsion was unjustified,¹³⁻¹⁶ and that this Coulomb repulsion might stop hole condensation beyond hole-pair formation.

To test this idea, we introduced a hole-Coulomb interaction in a generalized t-J model, which we call the t-J- ϵ model,¹¹

$$H_{J\epsilon} = H_J + \frac{e^2}{\epsilon} \sum_{\langle i,j \rangle} (1 - n_i) \frac{1}{r_{ij}} (1 - n_j) \quad (2)$$

We have carried out Monte Carlo¹¹ (for $t = 0$) and Lanczos¹⁷ studies of this model and conclude that phase separation does not occur for physical values of J and ϵ , and that only hole pairs form for $t/J = 3$ (the high- T_C value). These hole pairs have a binding energy and an rms size which are quite similar to the observed high- T_C energy gap and coherence length ξ_0 , which suggests that this "t-J- ϵ " model of the superconductors may give a realistic microscopic description of the hole Cooper pairs of high- T_C .

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**THE 2D HEISENBERG
ANTIFERROMAGNET IN HIGH- T_c
SUPERCONDUCTIVITY, A REVIEW OF
NUMERICAL TECHNIQUES AND
RESULTS¹**

T. Barnes²

Numerical studies of the quantum Heisenberg antiferromagnet on a square lattice, which is a model of the magnetic properties of the undoped "precursor insulators" of the high-temperature superconductors, are reviewed. Zero and nonzero temperature properties are discussed and the numerical results of analytic calculations and experiment, where appropriate, are compared. Various algorithms used to obtain these results are also reviewed, and algorithm developments and improvements in computer technology which would be most useful for future numerical work in this area are discussed. Several outstanding problems which may merit further investigation are also described.

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1. Abstract of an invited "Caltech C3P White Paper," submitted to *Int. J. Mod. Phys. C*.
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**STATIC HOLE ENERGIES IN THE t-J
MODEL AND A t-J- ϵ MODEL OF THE
HIGH-TEMPERATURE
SUPERCONDUCTORS¹**

T. Barnes² and M. D. Kovarik³

In this paper we present Monte Carlo results for the energies of static holes in the t-J model. We consider the cases of zero, one, two, and four holes on square lattices of side $L = 4, 6$, and 8 and extrapolate these results to give estimates for the bulk limit. We find that the hole energies and finite size effects are in good agreement with spin wave theory. Our results are consistent with phase separation in the static limit of the t-J model, but indicate that the incorporation of long-range Coulomb repulsion between holes prevents phase separation. We find that hole pairs alone are bound for a certain range of dielectric constant ϵ , which is $52 < \epsilon < 104$ in the static limit of a t-J- ϵ model with $1/r$ Coulomb repulsion, given the currently accepted value of J . The large observed value of the in-plane dielectric constant of La_2CuO_4 , $\epsilon = 30 \pm 3$, is not far from the lower limit of this theoretical pairing range, so the t-J- ϵ model may provide a useful approximate description of the mechanism of hole pairing in the high-temperature superconductors. Hole Cooper pairs which act as mediators of high-temperature superconductivity may thus arise from a competition between the large antiferromagnetic coupling J , which encourages hole clustering and the ϵ -suppressed hole Coulomb repulsion, which restricts hole binding to pairs.

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1. Abstract of paper: *Phys. Rev. B* 42, 6159 (1990).
 2. UT-ORNL Collaborative Scientist.
 3. Guest Assignee from University of Tennessee Knoxville.

8. COMPILATIONS AND EVALUATIONS

CONTROLLED FUSION ATOMIC DATA CENTER

H. B. Gilbody ¹	E. W. McDaniel ²
D. C. Gregory	F. W. Meyer
C. C. Havener	T. J. Morgan ³
H. T. Hunter	R. A. Phaneuf
M. I. Kirkpatrick	M. S. Pindzola ⁴
E. W. Thomas ²	

The Controlled Fusion Atomic Data Center (CFADC) collects, reviews, evaluates and recommends numerical atomic collision data which is relevant to controlled thermonuclear fusion research. The CFADC operates with an equivalent of 1.4 full-time staff members and a number of expert consultants under contract. Members of the experimental atomic physics for fusion group also contribute a small fraction of their time to literature searches and categorization of relevant publications.

The major activities of the CFADC are the following:

- the maintenance of an on-line computer bibliographic data base of fusion-related publications on atomic collision processes, and periodic distribution of updates to other data centers.
- the preparation and publication of compilations of recommended atomic collision data for fusion applications.
- the deduction of scaling laws and parametrizations of atomic collision data to facilitate application in fusion research.
- the establishment and dissemination of a computer data base of recommended collision cross sections and rate coefficients.
- the review of the existing atomic collision data base with respect to current applications in fusion research and identification of data needs.
- the handling of individual requests for specific data or literature searches on specific processes.

The CFADC participates in the Atomic and Molecular Data Center Network established by the International Atomic Energy Agency (IAEA) in

Vienna and has cooperative agreements with a number of other data centers. Bibliographic updates are sent semiannually on computer diskettes to the IAEA and to Japanese data centers at Nagoya and JAERI. This forms the basis for the semiannual IAEA *International Bulletin on Atomic and Molecular Data for Fusion*.

During this period, the major activity in the ORNL Controlled Fusion Atomic Data Center has been the completion, publication and distribution of the compilation of recommended data, entitled: "Atomic Data for Fusion, I: Collisions of H, H₂, He and Li Atoms and Ions with Atoms and Molecules," by C. F. Barnett (ORNL-6086). This volume contains recommended cross-section and rate-coefficient data for 321 different heavy-particle collision processes. An ALADDIN data base⁵ was also created for this volume and distributed on a PC-DOS diskette. Several new process labels were added to the ALADDIN dictionary, in coordination with the IAEA Atomic and Molecular Data Unit. A "README" help file was also created and distributed on the diskette to facilitate the adoption of the ALADDIN system by users.

At the request of the IAEA Atomic and Molecular Data Unit, cross-section data for ion-atom collision processes which play important roles in the edge plasma of magnetically confined fusion devices were surveyed and reviewed for publication in a Special Supplement to *Nuclear Fusion*.

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2. Consultant, Georgia Institute of Technology, Atlanta.
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4. Consultant, Auburn University, Auburn, AL.
5. R. A. Hulse, "The ALADDIN Atomic Physics Database System," pp. 63-72 in *Atomic Processes in Plasmas*, AIP Conference Proceedings 206, Y. K. Kim and R. C. Elton, eds., AIP, New York (1990).

NUCLEAR DATA PROJECT

*Y. A. Akovali, M. R. Lay, M. J. Martin, and
M. R. Schmorak*

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 $A \geq 199$. 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 14 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.

Activities

Data Evaluation. During this report period, NDP staff members prepared revised evaluations for the $A = 209, 217, 221, 232,$ and 239 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 17 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.

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.

9. PHYSICS WITH RADIOACTIVE BEAMS AT THE HOLIFIELD FACILITY

G. D. Alton
C. Baktash
H. K. Carter¹
D. T. Dowling
J. D. Garrett
D. L. Haynes
D. J. Horen
C. M. Jones

R. C. Juras
S. N. Lane
I. Y. Lee
M. J. Meigs²
G. D. Mills
S. W. Mosko
D. K. Olsen
B. A. Tatum

K. S. Toth

INTRODUCTION

The combination of the existing Oak Ridge Isochronous Cyclotron (ORIC) and 25-MV tandem accelerator provides a unique opportunity for producing low-energy, proton-rich radioactive heavy-ion beams for nuclear structure and astrophysics studies. An intense light-ion beam from ORIC, originally designed for a 1-mA, 65-MeV proton beam, would produce radioactive isotopes via fusion reactions in thick targets. Using the Isotope Separator On Line (ISOL) technique,³ the basis of existing isotope separators such as UNISOR,⁴ ISOLDE,⁵ and the radioactive beam acceleration facility at Louvain-la-Neuve,⁶ a radioactive beam would be produced for reacceleration in the tandem. Since both accelerators exist at HHIRF, as does an appropriately shielded target room for the ISOL source, the HHIRF provides a quick, cost-efficient method for producing radioactive beams.

The use of the HHIRF tandem accelerator, designed to accept low-energy, negatively-charged heavy ions, as the postaccelerator of such a facility allows heavy-ion beams up to mass 80 to be accelerated above the Coulomb barrier. The expected intensity and energy of a few ions that could be accelerated are given in Table 9.1. More than 200 new proton-rich compound systems with: up to seven neutrons less than can be produced with stable beams and targets; up to twelve neutrons beyond the proton drip line; and as heavy as ²¹²Np can be produced using stable targets and the beams listed in Table 9.1.

Table 9.1. Estimated maximum accelerated beam intensities, energies, and isospin for selected radioactive ion beams

Isotope	Tz	Intensity (10 ⁹ ions/s)*	Energy (MeV/amu)
14O	-1	3.1	13.0
15O	-1/2	2.5	13.0
17F	-1/2	47.	12.7
18F	0	21.	12.3
29P	-1/2	16.	8.6
30P	0	12.	8.4
30S	-1	1.2	8.4
31S	-1/2	0.24	8.2
68As	1	8.7	5.9
69As	3/2	10.	5.8
	2	10.	5.8
71As	5/2	10.	5.7
72As	3	4.8	5.6
73As	7/2	10.	5.5
74As	4	8.2	5.5
76As	5	1.2	5.3
70Se	1	1.3	5.8
71Se	3/2	.65	5.7
72Se	2	1.3	5.6

*1 pnA = 6.2 x 10⁹ ions/s.

PHYSICS OPPORTUNITIES

Measurements using radioactive beams provide a natural extension of the nuclear structure program of the Holifield Facility. Existing and planned ancillary equipment, including GAMMASPHERE, RMS, UNISOR, the Spin Spectrometer, the Dwarf Ball, the Oak Ridge BaF₂ Array, and the Oak Ridge spectrographs, are uniquely compatible with studies utilizing radioactive beams. A selection of the possible physics that might be addressed using this facility include:

Studies Near the ¹⁰⁰Sn Closed Shell. Detailed measurement of nuclear properties near the predicted double-closed shell nucleus, ¹⁰⁰Sn, such as the single-particle spectrum of states and empirical two-body residual interactions, will provide a stringent test of the microscopic independent-particle quantum structure forming the foundation of the nuclear shell model.

Rp-Process, p-Process and Hot CNO Cycle Nucleosynthesis. Detailed measurements of the properties of proton-rich, light- and medium-mass nuclei may provide sufficient information to determine the site, environment, and mechanism of rp-process, p-process and hot-CNO-cycle nucleosynthesis. For example, the path of rp-process nucleosynthesis, as shown in Fig. 9.1, follows the proton-rich nuclei that become accessible with the radioactive beams. Not only will this provide detailed nuclear structure information for rp-process nuclei, but several of the radioactive beams proposed for initial acceleration, such as ¹⁴O, ¹⁷F, ^{29,30}P, ^{30,31}S, and ⁶⁸As, occur as targets in the calculated rp-process path, allowing direct measurements of the appropriate reaction rates with inverse reactions.

New Regions of Normal, Super, Hyper, and Octupole Deformation. Several regions of exotic nuclear shapes will become accessible with the proton-rich radioactive beams thus providing detailed information on the single-particle basis of nuclear shapes. For example, it may be possible to study the predicted:

- Superdeformed states with $N, Z = 30 - 44$;
- Hyperdeformed states with $N, Z = 42, 44$, and 46;
- Octupole-deformed states with $N = Z = 30-34$ and 56;
- Triaxial self-conjugate medium-mass nuclei;
- Triaxial proton-rich heavy nuclei;

Nuclei with the largest predicted oblate deformation with $Z = 34-36$, $N = 33-38$;

Nuclei in which major shape modifications are predicted with the addition of a single nucleon, as shown in Fig. 9.2.

Studies of Nearly Self-Conjugate Nuclei Up to ¹⁰⁰Sn. With the proposed proton-rich beams it should be possible to study self-conjugate nuclei up to ¹⁰⁰Sn. In these nuclei, the single-particle effects are reinforced, since the neutrons and protons are filling the same single-particle states. Hence structural changes, such as deformations, as shown in Fig. 9.2, are predicted to change rapidly with N, Z , and angular momentum. Likewise, special isospin effects, such as superallowed beta decay between members of an isospin multiplet, and the Barshay-Temmer Relation governing the cross sections of reactions in which members of an isospin multiplet appear in the same reaction channel provide tests of isospin invariance.

Structure of Nuclei Near the Proton Drip Line. With the beams listed in Table 9.1, compound nuclei with $Z < 12$, $= 33, 35, 37$, and > 50 can be produced at or beyond the proton drip line. For heavy nuclei, compound systems can be formed with up to twelve neutrons (the bismuth isotopes) less than the predicted proton drip line. The Coulomb barrier, which inhibits the proton (and alpha) decay of these nuclei, provides a lifetime sufficiently long for nuclear structure studies of such intriguing proton-deficient nuclei.

Proton-Transfer Reactions with More Favorable Q-Values. A variety of new proton transfer experiments should become feasible with the improved Q-matching afforded by beams not currently available.

BEAM ENERGY AND INTENSITY

Radioactive Beam Energies. Because of its high terminal voltage, the tandem accelerator can accelerate 5-MeV/amu beams with high efficiency up to about mass 80. Figure 9.3 shows maximum energy and corresponding total transmission efficiency, including terminal stripping charge state fraction, for operation with terminal gas stripping and terminal foil stripping. A terminal potential of 26 MV was assumed with the charge state and charge state fraction taken at the peak of the charge state distribution. With terminal gas stripping, beams of

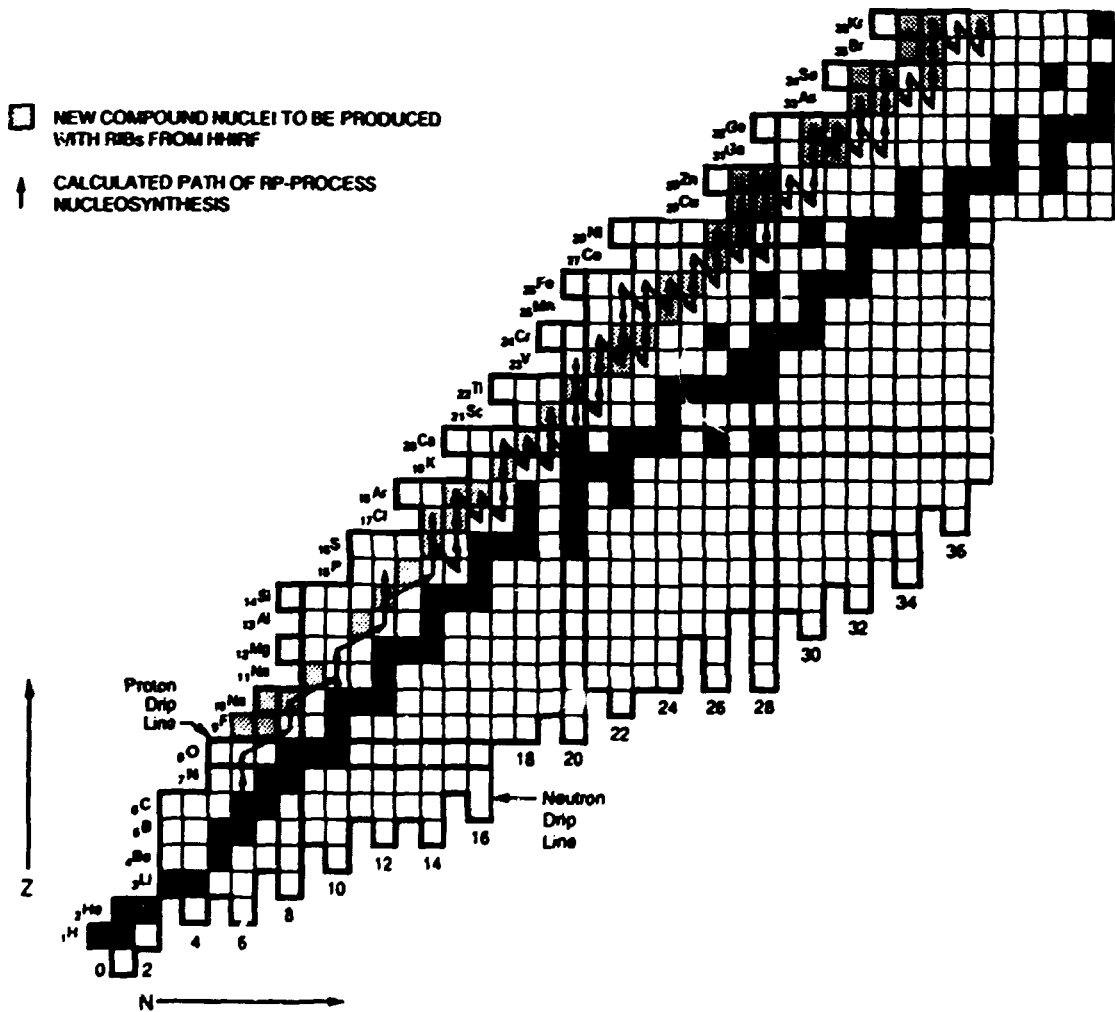


Fig. 9.1. Comparison of the "new" proton-rich compound nuclei (shaded squares) that can be produced by the proposed radioactive beam extension of the HHIRF and the predicted (M. Wiescher, private communication) path of the rp-process (arrows) for temperatures of 1.5×10^9 °K and proton densities of 10^4 g/cm³. Stable nuclei are shown as solid squares and the proton and neutron closed shells and drip lines are indicated by heavy lines.

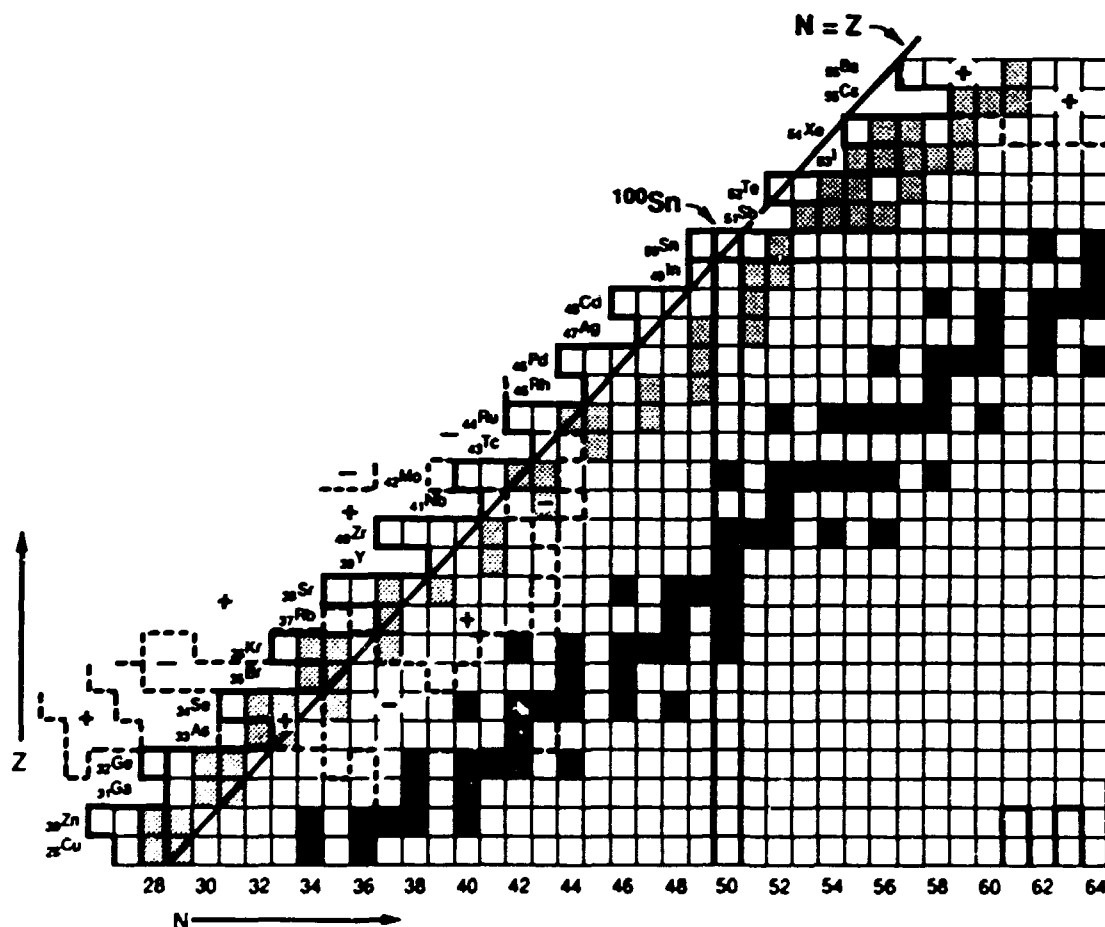


Fig. 9.2. The "new" proton-rich compound nuclei with $Z = 29-56$ (shaded squares) that can be produced by the proposed radioactive beam extension of the HHIRF and that cannot be produced by combinations of stable beams and targets. For comparison, the regions of proton-rich nuclei in which the nuclear ground state is predicted to be deformed ($\epsilon_2 > 0.20$ or < -0.20) are indicated by the heavy dashed lines with + and - signs denoting prolate and oblate deformation, respectively. Stable nuclei are shown as solid squares and the proton and neutron closed shells and drip lines are indicated by heavy solid lines. Likewise the line of self-conjugate nuclei ($N = Z$) is indicated, as is the location of the doubly closed shell nucleus ^{100}Sn .

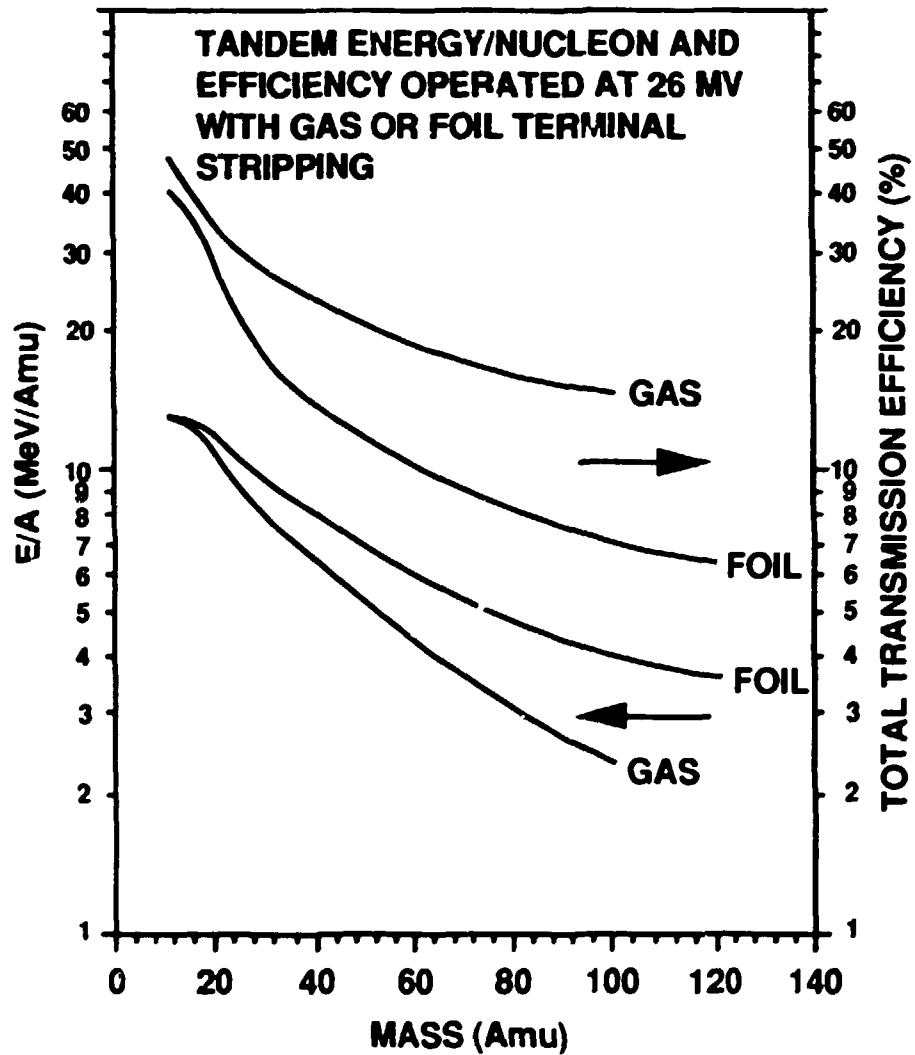


Fig. 9.3. Maximum beam energy per nucleon and total transmission efficiency of the most probable charge state for the tandem accelerator operated with gas and foil stripping with the terminal potential at 26 MV.

mass 52 can be accelerated above 5 MeV/amu with a total efficiency of 20%. With terminal foil stripping, beams of mass 80 can be accelerated above 5 MeV/amu with a total efficiency of 8%. In both cases, beams of lower masses can be accelerated to higher energies with total efficiencies approaching 50%.

It is important to appreciate that since the tandem accelerator is inherently a dc machine, no bunching is required for the injected beam. This property is perfect to maximize the low-intensity dc beams available from an ISOL source. In addition, the other inherent advantages of the tandem accelerator, such as simplicity, reliability, flexibility, and excellent accelerated beam quality, are also available. No modification to the tandem accelerator would be required for service as a radioactive beam postaccelerator.

The maximum radioactive ion beam currents are much more difficult to estimate and are, in general, the product of two factors: the production rate of radioactive atoms in a thick target and the conversion efficiency of these atoms to accelerated beam.

Production Rate of Radioactive Atoms. Radioactive atoms will be produced in thick targets by primary beams from ORIC. The maximum energy of these beams is limited by the ORIC bending power of $K = ME/Q^2 = 105$, as well as rf frequency and focusing limitations for protons. These limitations give maximum beam energies of: 55-MeV ^1H , 52-MeV ^2H , 140-MeV $^3\text{He}^{2+}$, 105-MeV $^4\text{He}^{2+}$, 70-MeV $^6\text{Li}^{2+}$, 60-MeV $^7\text{Li}^{2+}$, 94-MeV $^{10}\text{B}^{3+}$, and 86-MeV $^{11}\text{B}^{3+}$. The available intensity of H and He beams is presently believed to be limited by heat dissipation and activation in the beam extraction system, specifically the septum of the electrostatic deflector. A maximum value of 1 kW for heat dissipation in the deflector septum and a beam extraction efficiency of 67% are assumed, giving an extracted beam power of 2 kW, independent of energy. It is also believed that the available intensity of Li and B beams will be ion-source limited to about 10 μA . It should be emphasized that these beam intensity limits are not absolute. Beams with these intensities were obtained in the early 1960s and future development work could result in larger beam intensities, if required.

With these intensities, thick target production rates for radioactive atoms were estimated using a cross-section model based on nuclear systematics along with the stopping powers of Northcliffe and

Schilling.⁷ Production rates for proton-rich beams as heavy as ^{83}Rb were calculated using (H, xn) (He, xn), (Li, xn), and (B, xn) reactions on C, N, O, Si, and Ge targets. Carbon is an ideal high-temperature target. High-temperature N, O, and Si targets are available as refractory ceramics. ISOLDE has used both liquid Ge targets and Zr_5Ge_3 compound which has a melting point of about 2300°C. Other target elements are, of course, also possible. The cross sections were scaled, as demonstrated by M. Kaplan⁸ from the measured (p, xn) and (α , xn) results of Refs. 9-12. Some of these scaled cross sections could be uncertain by as much as a factor of four. The thick target production rate of ^{14}O from the (p,n) reaction on a BN target with 27-MeV protons from the tandem accelerator was, in fact, measured by counting 2.3-MeV ^{14}N gamma rays after target radiation.

Conversion Efficiency of Atoms to Beam. The overall conversion efficiency from radioactive atoms to accelerated beam, excluding decay and target release losses, for all elements between C and Pb, were estimated. Two methods are possible for negative ion formation: direct-surface ionization and charge exchange. The direct-surface negative ionization technique is applicable to elements with large electron affinities, greater than about 2 eV, such as F, Cl, Br, S, and Se. For these elements, conversion efficiencies were estimated from the Langmuir-Saha relation for a LaB_6 surface ionizer work function ($\phi = 2.36$ eV) operated at 1370°K. The efficiency was taken to be 50% of this calculated value.

Conversion efficiencies from atoms to negative ions using the charge-exchange technique are the product of the conversion efficiency from atoms to positive ions and the conversion efficiency of positive ions to negative ions. The efficiencies for converting neutral radioactive atoms into positive ions were estimated by scaling the probability for electron impact ionization of the species in question to that of calcium for which the efficiency has been measured to be 30%.¹³ The conversion efficiencies from positive to negative ions through sequential charge exchange were based on experimental measurements by Heinemeier and Hvelplund¹⁴ for Na and Mg exchange vapors and on measured values by Greenway for Cs exchange vapor as reported in Ref. 15.

Although beam transport from the direct ionization source or charge exchange cell through the mass separator to the tandem accelerator is expected

to be efficient, a 50% loss factor was also included to account for anomalous losses in this transport and elsewhere. The total tandem accelerator efficiencies were taken from Fig. 9.3. The results are very encouraging. With the assumptions described above, 21 of the 32 elements between C and Rb have an estimated overall conversion efficiency of the order of 10^{-3} or greater and could be readily accelerated as beam. This table, of course, does not contain any decay losses for short-lived isotopes and assumes a 100% release efficiency of radioactive atoms from the target material.

Beam Intensities. Some of the more interesting and intense beams are listed in Table 9.1 which shows that the proposed technique appears to have great promise. Many beams have intensities greater than 1.0 pA. It is also important to note that the maximum required primary beam energies are generally quite low. These low energies will result in low ORIC operating costs and low system activation. Finally, it should be emphasized that this preliminary study is addressed only to the general potential of the technique. Decay losses and release rate losses have not been considered. For some beams, such as ^{30}S , these losses could be large. However, there is good reason to believe that the development program which would accompany a radioactive beam program would minimize these losses and provide a wide variety of intense radioactive beams.

ADDITIONAL EQUIPMENT

Very little additional equipment would be required to produce radioactive beams with the HHIRF. The shielding for the original ORIC facility was designed for 75-MeV, 1-mA proton beam; consequently, the ORIC vault and the original ORIC target areas are shielded to this original standard. These rooms are also equipped with single-pass HVAC systems appropriate for high-radiation areas. One of these rooms, C-111, would house the ISOL target-ion source and mass separator, as well as the associated storage caves and remote handling equipment that may be required for the irradiated target-ion sources. This room is 20 feet wide, 34 feet long, and has two five-foot-thick steel access doors. While modest arrangement of stacked block shielding would be necessary, no civil construction would be required. Except for a necessary change in

elevation, the high-voltage platform could be fed by an existing 43-foot-long beam line from ORIC.

The additional equipment required to produce radioactive beams at the HHIRF is shown in Figs. 9.4 to 9.6. Figure 9.4 shows the ISOL target-ion source and mass separator located on a high-voltage platform, situated in the south end of Room C-111. The high-voltage platform would be operated at potentials up to 280 kV, with respect to building ground; and, in conjunction with the ISOL source potential of 20 to 80 kV, with respect to platform ground, would provide the nominal 300 keV energy presently used for tandem injection. ORIC beams would be transported from ground potential to the platform, and the ISOL source, through an acceleration tube. Depending on the element, either positive or negative ions would be formed in the ISOL source. These ions would be accelerated to platform potential, gaining 20 to 80 keV, and then transported through a 90° analyzing magnet where ions of the desired mass would be selected. This mass-analyzed beam would then be transported through the charge exchange cell, if required, and through an acceleration tube to ground potential. At this point, the beam would be ready for injection into the tandem accelerator. The new apparatus on the platform would be somewhat similar to that already used at UNISOR. As shown in Fig. 9.4, the north end of Room C-111 could, if required, be configured as an ion source service area with appropriate shielding and remote-handling equipment.

Figures 9.5 and 9.6 show the beam line to transport negative ions through the east experimental area, Room T-106, from the high-voltage platform to the tandem accelerator. This transfer line would be located at an elevation of 7.5 feet above the local floor level. Injection into the tandem accelerator would be accomplished by merging the beam through the existing, de-energized, mass-analyzing magnet as shown in Fig. 9.6. A second mass analysis would be performed on the negative ion beam prior to tandem injection with the 65° magnet shown in Fig. 9.5. The negative-ion beam transfer line will use components identical to, or very similar to, those used in the existing tandem injection line and will be of all-metal construction. This beam line will be pumped with sputter ion pumps, and operating pressures in the low 10^{-8} Torr range are expected.

CRNL-DWG 90-17356

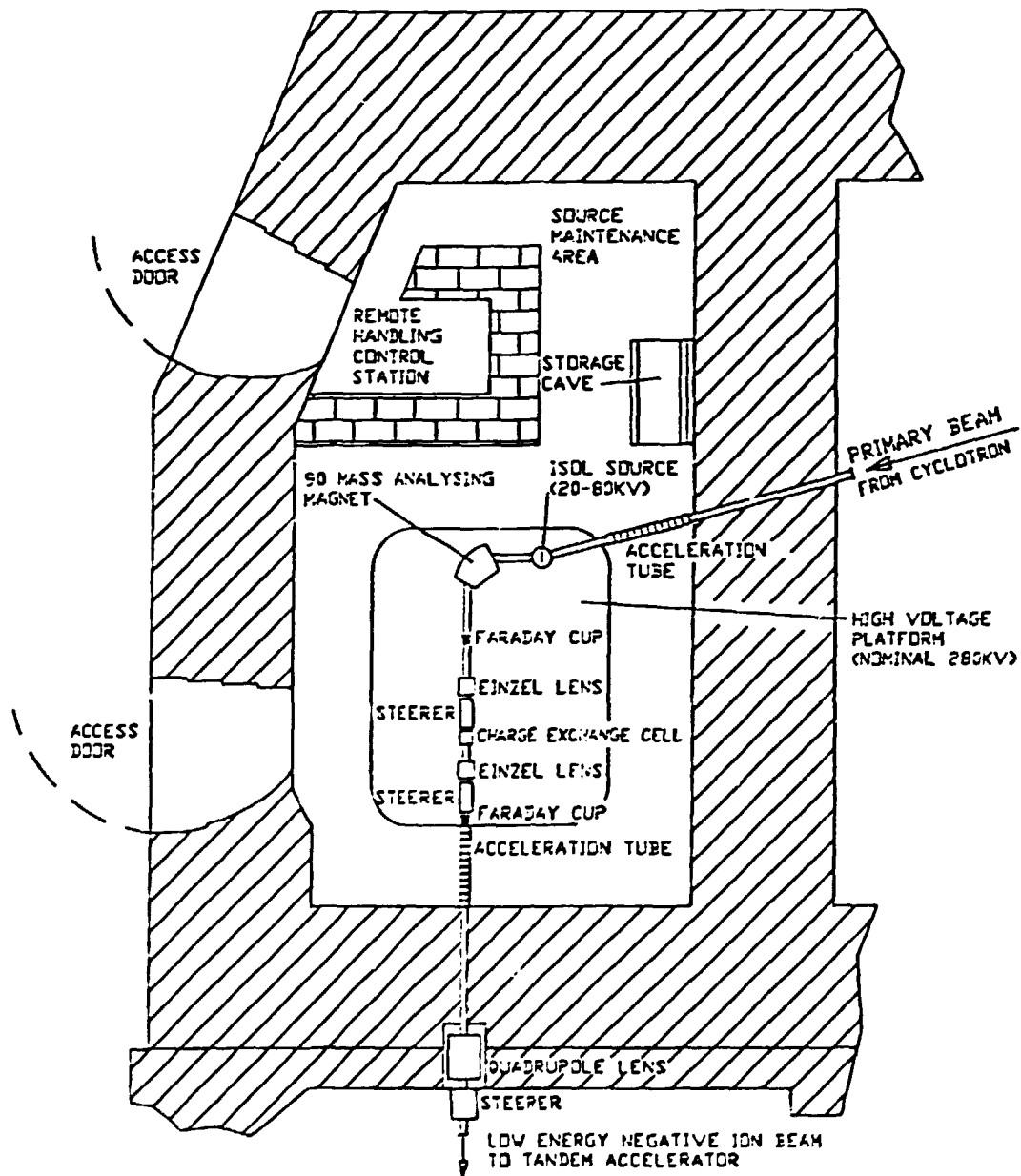


Fig. 9.4. Plan view of target room C-111 showing details of the proposed radioactive beam facility high-voltage platform and source maintenance area.

ORNL-DWG 90-17397

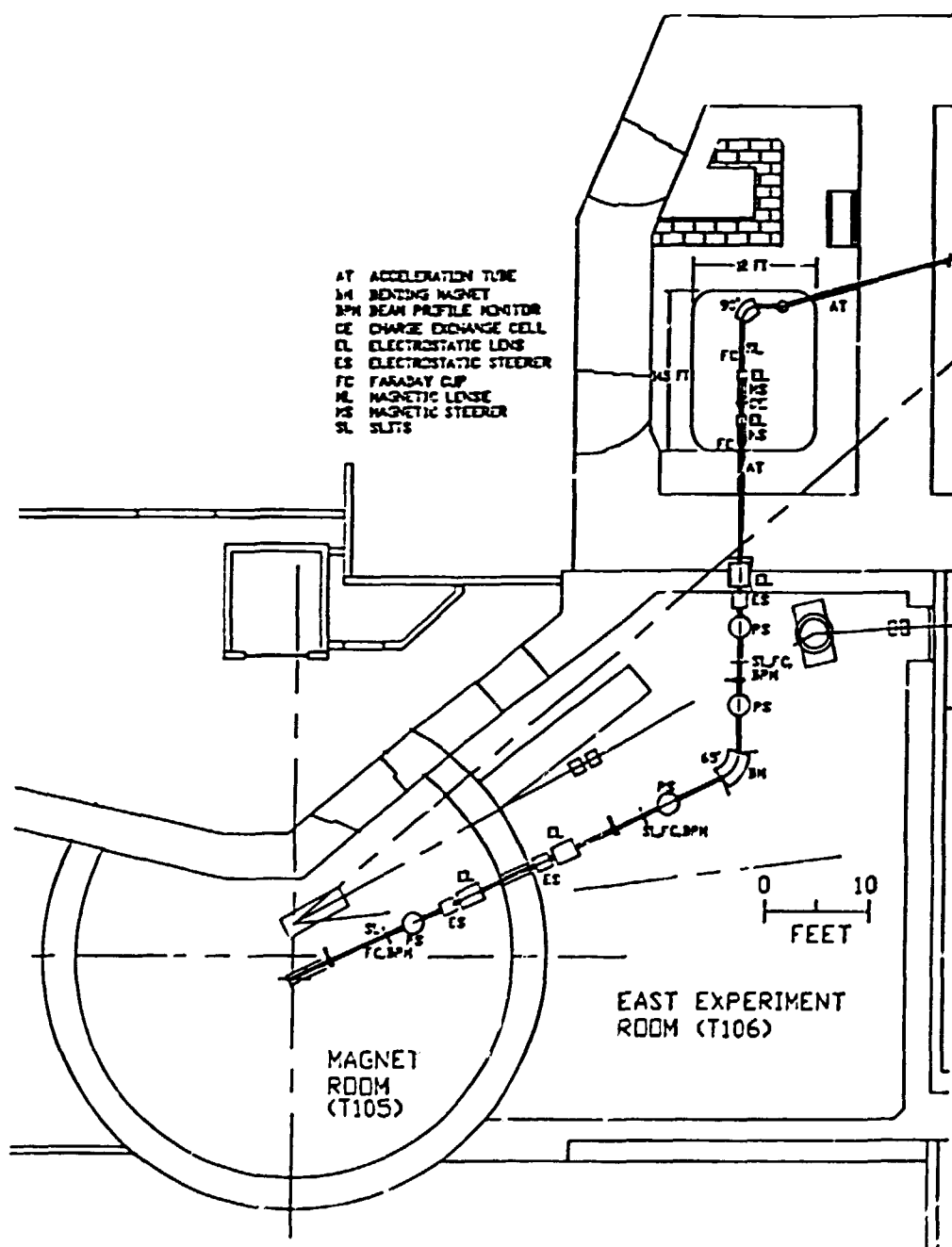


Fig. 9.5. Plan view of the proposed radioactive beam facility high-voltage platform and negative ion transfer line.

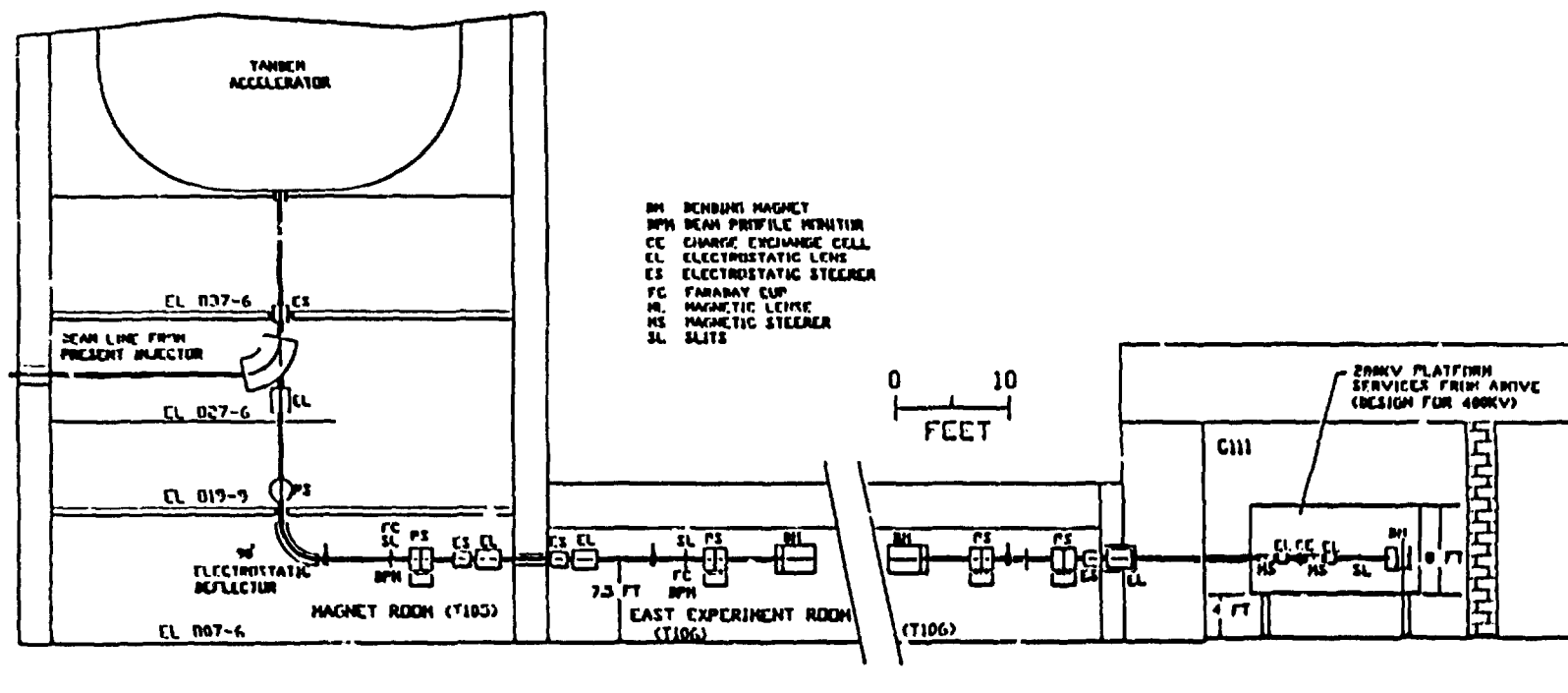


Fig. 9.6. Elevation view of the proposed radioactive beam facility high-voltage platform and negative ion transfer line.

Controls for components on the ISOL high-voltage platform and the negative ion beam transfer line would be provided by a straightforward extension of the existing tandem accelerator CAMAC-based control system. Since the tandem accelerator is now equipped with two independent control consoles, one of these could easily be used for ISOL operations. It is important to note that the proposed ISOL system could be operated independently of the tandem accelerator, so that radioactive beams could be developed off-line without disturbing conventional tandem-only operation.

The most important piece of equipment for producing radioactive beams with the HHIRF is, of course, the ISOL target-ion source. The detailed choice of target type and composition, ion source type, materials and geometry, component operating temperatures, possible support gases, etc. depend on the desired radioactive beam and target isotope. Clearly, the general techniques developed at the ISOLDE facility, UNISOR, and other on-line isotope separators, are directly applicable. The specific techniques required for a low-energy, light-ion primary beam producing relatively light radioactive ions in thick targets will require considerable research and development. The existing UNISOR facility and the ability of the tandem accelerator to produce beams of any element desired as a radioactive beam allow this research and development to proceed in an expeditious manner.

COST ESTIMATE AND SCHEDULE

A preliminary cost estimate to extend the HHIRF to produce radioactive beams is \$3.5M. This includes modifications to ORIC, a high-voltage platform for the isotope separator, beam lines, and modification of the existing shielded target room which would house the isotope separator. It is estimated that low-intensity beams could be available within 12 months of funding. High-intensity beams could be available within 24 months of funding. More details of this study can be found in Ref. 16.

1. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

2. Instrumentation and Controls Division, ORNL.

3. H. L. Ravn and W. Allardyce, "On-Line Mass Separators" in *Treatise on Heavy Ion Science*, ed. D. A. Bromley (Plenum Press, New York, 1989), Vol. 8, p. 363.

4. E. H. Spejewski et al., *Nucl. Instr. and Meth.* **186**, 71 (1981).

5. R. W. Allardyce et al., *Nucl. Instr. and Meth.* **B26**, 112 (1987).

6. D. Darquennes et al., *Phys. Rev. C* **42**, 805 (1990).

7. L. C. Northcliffe and R. F. Schilling, *Nuclear Data Tables A7*, 233 (1970).

8. M. Kaplan, *Phys. Rev.* **143**, 894 (1966).

9. S. M. Read and V. E. Viola, Jr., *Atomic Data and Nuclear Data Tables* **31**, 359 (1984).

10. E. M. Rimmer and P. S. Fisher, *Nucl. Phys. A* **108**, 561 (1967).

11. C. Wong et al., *Phys. Rev.* **156**, 1266 (1967).

12. T. McGee et al., *Nucl. Phys. A* **150**, 11 (1970).

13. J. G. Tracy, private communication.

14. J. Heinemeier and P. Hvelplund, *Nucl. Instr. and Meth.* **148**, 65 (1978) and *Nucl. Instr. and Meth.* **148**, 425 (1978).

15. G. L. Alton, *Proc. Int. Workshop on Spin Polarized Sources and Gas Jets, KEK Tsukuba, Japan, Feb. 12-17, 1990*. (In press.)

16. "Physics with Radioactive Beams at the Holifield Heavy Ion Research Facility," ed. J. D. Garrett and D. K. Olsen, working draft, October 1990.

THICK TARGET YIELD MEASUREMENTS FOR ^{10}C AND ^{14}O RADIOACTIVE BEAMS

I. Y. Lee W. B. Gao
D. K. Olsen

As an initial step to determine the feasibility of producing radioactive beams with the HHIRF accelerators, the thick target yields of ^{10}C and ^{14}O were measured with proton beams from the tandem accelerator. A thick boron nitride (BN) target was bombarded with 20- and 25-MeV proton beams with an intensity of 0.2 nA. The yields of the $^{10}\text{B}(p,n)^{10}\text{C}$ and $^{14}\text{N}(p,n)^{14}\text{O}$ reactions were determined from the gamma-ray yields of their beta-decay products. Since the half-life of ^{10}C and ^{14}O are 19.2 s and 70.6 s respectively, the measurements were carried out using several cycles of three-minute beam on target and three-minute beam off counting. As shown in Fig. 9.7, the 718-keV 1^+ to 3^+ transition in ^{10}B produced in the beta decay of ^{10}C and the 2313-keV 0^+ to 1^+ transition in ^{14}N from the beta decay of ^{14}O were observed. From the gamma ray yields, together with the known counting time, beam intensity, and the absolute efficiency of the detector, the production yields were determined. The results listed in Table 9.2 indicate that the yields are about 10^9 radioactive atoms per microamp of beam, which are consistent with expectations.

Table 9.2. Production yield per microamp of proton beam on a BN target

E_p (MeV)	$^{10}\text{B}(p,n)^{10}\text{C}^*$	$^{14}\text{N}(p,n)^{14}\text{O}$
20	0.8×10^9	0.35×10^9
25	1.5×10^9	0.39×10^9

*Assumes 100% enriched ^{10}B target.

ORNL-DWG 90-17646

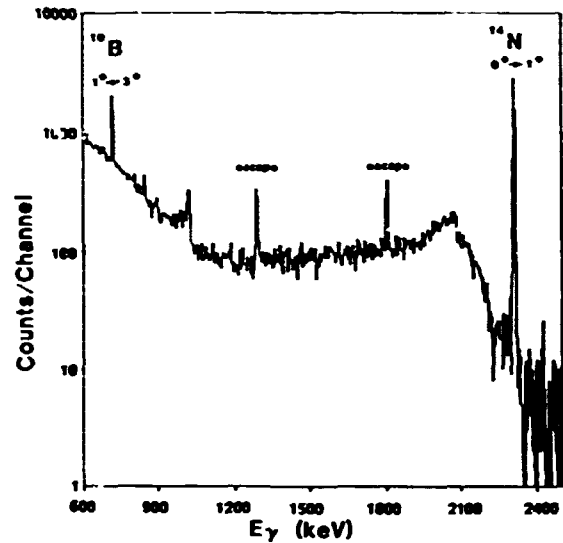


Fig. 9.7. Out of beam γ ray spectrum for the reaction $P + \text{BN}$ measured in a Ge detector.

10. PUBLICATIONS

List Prepared by Shirley J. Ball

The following list of publications includes primarily those articles by Physics Division staff members and associates which appeared in print from October 1989 through September 1990. Articles pending publication as of September 30, 1990, are listed immediately following this section.

BOOK, JOURNAL, AND PROCEEDINGS ARTICLES

Akovali, Y. A.

"Nuclear Data Sheets for A = 229," Nucl. Data Sheets 58, 555-88 (Oct. 1989)

Akovali, Y. A.

"Nuclear Data Sheets for A = 233," Nucl. Data Sheets 59, 263-331 (Jan. 1990)

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Thoennessen, M.

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Thoennessen, M., J. R. Beene, R. L. Auble, F. E. Bertrand, C. Baktash, M. L. Halbert, D. J. Horen, C. A. Ludemann, D. G. Sarantites, D. W. Stracener, and W. Spang

"Observation of Entrance Channel Effects in Compound Nucleus Formation with High Energy γ -Rays," Proceedings, Workshop on the Interface Between Nuclear Structure and Heavy-Ion Reaction Dynamics, Notre Dame, Indiana, May 24-26, 1990

Thompson, J. S., D. J. Pegg, J. Dellwo, R. N. Compton, and G. D. Alton (Invited Presentation)

"Photodetachment of Metastable He^+ ," Proceedings, XI International Conference on the Application of Accelerator in Research and Industry, Denton, Texas, November 5-8, 1990

Tincknell, M. L. (Invited Presentation)

"Investigation into the Feasibility of a Soft Muon Experiment," Proceedings, Workshop on Heavy-Ion Physics at the AGS, Upton, New York, March 5, 1990

Toth, K. S., D. M. Moltz, J. M. Nitschke, and P. A. Wilmarth (Invited Presentation)

"Heavy Ions as Probes of Nuclei Far from Stability," Proceedings, International School-Seminar on Heavy Ion Physics, Dubna, U.S.S.R., October 3-12, 1989

Toth, K. S., D. M. Moltz, J. M. Nitschke, P. A. Wilmarth, and J. D. Robertson (Invited Presentation)

"Spectroscopic Studies Near the Proton Drip Line," Proceedings, Symposium on Capture Gamma-Ray Spectroscopy, Asilomar, California, October 15-19, 1990

Toth, K. S., J. M. Nitschke, K. S. Viirinen, P. A. Wilmarth, R. B. Firestone, and M. O. Kortelahu (Invited Presentation)

"Spectroscopy of Proton-Rich Nuclei in the Rare Earth Region," Proceedings, International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 5-8, 1990

- Toth, K. S., J. M. Nitschke, P. A. Wilmarth, and K. S. Vierinen (Invited Presentation)
 "Nuclear Spectroscopy in the Rare Earth Region Near the Proton Drip Line," Proceedings, 1989 Meeting of the American Chemical Society, Miami Beach, Florida, September 10-15, 1989
- Toth, K. S., D. C. Sousa, J. M. Nitschke, K. S. Vierinen, P. A. Wilmarth, and M. O. Kortelahti
 "Single-Particle States in the Rare Earth Region Near the Proton Drip Line," Physics Letters B
- Umar, S., and M. R. Strayer
 "Numerical Methods for Nuclear Mean-Field Dynamics," Computer Physics Communications
- Umar, A. S., J. R. Wu, M. R. Strayer, and C. Botcher
 "Basis-Spline Collocation Method for the Lattice Solution of Boundary Value Problems," Journal of Computational Physics
- Underwood, T. A., M. Breinig, and C. C. Gaither
 "Production of 'Doubly Excited' Projectile States in Collisions of 0.1 MeV/u Ag^{4+} Ions with He, H_2 , and Ar Targets," Physical Review A
- Utsunomiya, H., Y.-W. Lui, D. R. Haenni, H. Dejbakhsh, L. Cooke, B. K. Srivastava, W. Turmel, D. O'Kelley, R. P. Schmitt, D. Shapira, J. Gomez del Campo, A. Ray, and T. Udagawa
 "Breakup of ^7Li Near the α -t Threshold and a Possible Probe of Radiative Capture Process," Physical Review Letters
- Varner, R. L., W. J. Thompson, R. L. McAbee, E. J. Ludwig, and T. B. Clegg
 "A Global Nucleon Optical Model Potential," Physics Reports
- Wahlin, E. K., J. S. Thompson, G. H. Dunn, R. A. Phaneuf, D. C. Gregory, and A.C.H. Smith
 "Electron Impact Excitation of Multiply-Charged Ions Using Energy Loss in Merged Beams: $e + \text{Si}^{3+}(^2\text{S}_{1/2}) \rightarrow e + \text{Si}^{3+}(^2\text{P}_{1/2,3/2})$," Proceedings, Vth International Conference on the Physics of Highly Charged Ions, Giessen, West Germany, September 10-14, 1990
- Wang, J., J. Burgdorfer, and A. Barany
 "Ionization Spectrum for Ion-Atom Collisions with Zero-Range Potentials in One and Three Dimensions," Physical Review A
- Welton, T. A.
 "On the Origin of Gravitational Effects," Physical Review
- Wong, C. Y., R. C. Wang, and C. C. Shih
 "A Study of Particle Production Using Bosonized QED2," Physical Review D
- Woody, C., D. Lissauer, J. Gomez del Campo, A. Ray, D. Shapira, M. Tincknell, R. Clark, C. Erd, J. Schurkraft, and W. Willis
 "Status of Soft Photons in Experiment E855," Proceedings, Workshop on Soft Lepton Pair and Photon Production, Pittsburgh, Pennsylvania, September 6-8, 1990
- Wu, J. S., C. Botcher, M. R. Strayer, D. J. Ernst, and A. K. Kerman
 "Coherent Particle Production from Relativistic Heavy-Ion Collisions," Proceedings, Second International Conference on Medium- and High-Energy Nuclear Physics, Taiwan, Republic of China, May 8-12, 1990
- Wu, J. S., C. Botcher, M. R. Strayer, and A. K. Kerman
 "Coherent Higgs and $W^\pm$ Pair Production," Annals of Physics (N.Y.)

Wyss, R., and A. Johnson

"Unexpected Alignment Patterns in High-J Intruder Bands; Evidence for a Strong Residual Neutron Proton Interaction?," Proceedings, International Conference on High Spin Physics and Gamma-Soft Nuclei, Pittsburgh, Pennsylvania, September 17-21, 1990

Wyss, R., and S. Pilotte

"Integer Alignment and Strong Coupling Limit in Superdeformed Nuclei," *Physical Review C*.

Yang, X., J. Burgdorfer, E. Eschenazi

"On the Morphology of Avoided Crossings in the Spectrum of Irregular Quantum Systems," Proceedings, Miniworkshop on Quantum Chaos, Trieste, Italy, June 4-July 6, 1990

Yang, X., and J. Burgdorfer

"Molecular Dynamics Approach to the Statistical Properties of Energy Levels," *Physical Review Letters*

Young, G. R. (Invited Presentation)

"Experimental Results from Studies of Nucleus-Nucleus Collisions at High Energy," Proceedings, American Physical Society, Division of Particles and Fields, Houston, Texas, January 3-6, 1990

Young, G. R. (Invited Presentation)

"Experimental Results Concerning Global Observables from the CERN SPS Heavy Ion Program," Proceedings, Workshop on Heavy-Ion Physics at the AGS, Upton, New York, March 5, 1990

Zeijlmans van Emmichoven, P. A., C. C. Havener, and F. W. Meyer

"The Neutralization of Highly Charged Ions Grazingly Incident on a Metal Surface," *Physical Review A*

Zeijlmans van Emmichoven, P. A., C. C. Havener, F. W. Meyer, and D. M. Zehner (Invited Presentation)

"Electron Emission During Multicharged Ion-Surface Interactions," Proceedings, XI International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 5-8, 1990

11. PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS

October 1989 Through September 1990

List Prepared by Shirley J. Ball

1989

**7th APS Topical Conference on Atomic Processes in Plasmas, Gaithersburg, Maryland,
October 2-5, 1989**

Barnett, C. F., D. C. Gregory, H. T. Hunter, M. I. Kirkpatrick, R. A. Phaneuf, A. Musgrove, and W. L. Wiese

"Atomic Data for Fusion"

Chantrenne, S., C. D. Gregory, D. Schneider, M. Prior, and R. Hutton

"Triple Electron Capture and Double Auger Decay in Slow Collisions of O^{7+} on Argon and Krypton"

Gregory, D. C., D. W. Mueller, and H. Tawara

"Dissociation and Ionization of CD_4^+ by Electron Impact"

Havener, C. C., M. P. Nesnidal, and R. A. Phaneuf

"Low-Energy Cross Section Measurements for Electron Capture by Multicharged Oxygen Ions from Atomic Hydrogen and Deuterium"

Workshop on the Nucleus at High Spin, Copenhagen, Denmark, October 2-27, 1989

Garrett, J. D. (Invited Presentation)

"New Ways to Look at Old (and New) Data"

**International School-Seminar on Heavy Ion Physics, Dubna, U.S.S.R., October 3-12,
1989**

Toth, K. S. (Invited Presentation)

"Heavy Ions as Probes of Nuclei Far from Stability"

**American Physical Society, Division of Nuclear Physics, Pacific Grove, California,
October 12-14, 1989**

Akovali, Y. A., H. K. Carter, W. D. Hamilton, I. C. Girit, J. Breitenbach, C. R. Bingham, W. Schmitt-Ott, R. L. Knight, J. M. Bauer, J. A. Becker, E. A. Henry, R. A. Meyer, and J. Kornicki

"Search for Low-Spin Superdeformed States in ^{188}Hg and ^{186}Hg ," Bull. Am. Phys. Soc. 34, 1816 (Sept. 1989)

Bingham, C. R., H. V. Carmichael, L. L. Riedinger, P. B. Semmes, H. K. Carter, C. Girit, R. A. Braga, J. L. Wood, and E. F. Zganjar

"The Interpretation of States Based on the Low-Lying $9/2^-$ State in ^{195}Tl in Terms of Particles Coupled to Triaxial Rotor and IBA Cores," Bull. Am. Phys. Soc. 34, 1817 (Sept. 1989)

Braga, R. A., J. L. Wood, B. D. Kern, J. Kormicki, and M. O. Kortelahi

"Decay of Mass-Separated ^{137}Eu and ^{137}Sm ," Bull. Am. Phys. Soc. 34, 1823 (Sept. 1989)

Gross, E. E., D. C. Hensley, and J. R. Beene

"Hyperfine Precession of Scattered $^{24}\text{Mg}(11^+)$ Ions," Bull. Am. Phys. Soc. 34, 1818 (Sept. 1989)

Hamilton, W. D., H. Marshak, and K. Kumar

"Can Existing Nuclear Models Predict the Change of Signs of E2/M1 Mixing Ratios in Well Deformed Nuclei?," Bull. Am. Phys. Soc. 34, 1825 (Sept. 1989)

Horen, D. J., F. E. Bertrand, J. R. Beene, W. Mittig, A.C.C. Villari, Y. Schutz, Z. Wenlong, E. Plagnol, and A. Gillibert

"Measurement of Mn/mP for the GQR in ^{118}Sn ," Bull. Am. Phys. Soc. 34, 1833 (Sept. 1989)

Jin, H. Q., C. R. Bingham, M. P. Carpenter, V. P. Janzen, L. L. Riedinger, L. Zhou, C. Baktash, M. L. Halbert, N. R. Johnson, I. Y. Lee, F. K. McGowan, and M. A. Riley

"High-Spin States in $^{179,181}\text{Ir}$," Bull. Am. Phys. Soc. 34, 1825 (Sept. 1989)

Kumano, S., and F. E. Close

"Dependence of the EMC Effect on Nuclear Structure," Bull. Am. Phys. Soc. 34, 1814 (Sept. 1989)

Lee, I. Y., C. Baktash, N. R. Johnson, F. K. McGowan, W. B. Gao, J. H. Hamilton, Y. R. Jiang, and S. Zhu

"Study of High Spin States in ^{169}Hf and ^{170}Hf ," Bull. Am. Phys. Soc. 34, 1825 (Sept. 1989)

Mantica, P. F., Jr., B. E. Zimmerman, W. B. Walters, D. Rupnik, E. F. Zganjar, W. L. Croft, Y. S. Xu, and H. K. Carter

"The Decay of ^{127}Cs ," Bull. Am. Phys. Soc. 34, 1807 (Sept. 1989)

Ray, A., D. Shapira, J. Gomez del Campo, H. J. Kim, M. L. Halbert, J. Sullivan, B. Shivakumar, and J. Mitchell

"Spin Alignment Measurement in $^{28}\text{Si} + ^{12}\text{C}$ Orbiting Reaction," Bull. Am. Phys. Soc. 34, 1818 (Sept. 1989)

Schwarzenberg, I., J. L. Wood, and E. F. Zganjar

"Decay of Mass-Separated ^{183}Au to ^{183}Pt ," Bull. Am. Phys. Soc. 34, 1825 (Sept. 1989)

Shea, J. Y., C. F. Maguire, R. Clark, D. Olive, J. H. Hamilton, D. Shapira, H. Kim, and B. Glagola

"An Organic/Inorganic Scintillator Ball Detector for Inverse Kinematics Heavy Ion Central Collisions," Bull. Am. Phys. Soc. 34, 1838 (Sept. 1989)

Shea, J. Y., C. F. Maguire, D. Shapira, H. Kim, K. Teh, J. P. Wieleczko, and M. Korolija

"Fusion of $^{58}\text{Ni} + ^{24}\text{Mg}$ at 10.9 MeV/Nucleon," Bull. Am. Phys. Soc. 34, 1819 (Sept. 1989)

Thoennessen, M., J. R. Beene, F. E. Bertrand, and J. L. Blankenship

"Performance of the Oak Ridge BaF₂ Project," Bull. Am. Phys. Soc. 34, 1838 (Sept. 1989)

Vierinen, K. S., J. M. Nitschke, P. A. Wilmarth, R. B. Firestone, R. M. Chasteler, and K. S. Toth

"Beta-Delayed Decay Studies of Lu, Yb, Tm, and Er Nuclei with $N > 82$ and $Z > 64$," Bull. Am. Phys. Soc. 34, 1807 (Sept. 1989)

Wieleczko, J. P., D. Shapira, H. Kim, J. Gomez del Campo, K. Teh, J. Shea, M. Korolija, C. Volant, and A. D'Onofrio

"Fusion and Complex Fragment Emission of $^{79}\text{Br} + ^{27}\text{Al}$ at 12 MeV/Nucleon," Bull. Am. Phys. Soc. 34, 1817 (Sept. 1989)

Zganjar, E. F., M. O. Kortelahti, J. L. Wood, C. R. Bingham, H. K. Carter, K. S. Toth, J. H. Hamilton, J. Kormicki, L. Chaturvedi, and W. B. Newbolt

"Shape Coexistence in ^{190}Hg ," Bull. Am. Phys. Soc. 34, 1816 (Sept. 1989)

First International Conference on Radioactive Beams, Berkeley, California, October 16-18, 1989

Hamilton, W. D. (Invited Presentation)

"A Fission Source of Radioactive Heavy Ions"

Raman, S.

"Predictions of Ground-State Deformations of Even-Even Nuclei"

NSF-EPRI Workshop on Anomalous Effects in Deuterated Metals, Washington, D.C., October 16-18, 1989

Hutchinson, D. P., C. A. Bennett, R. K. Richards, J. Bullock IV, and G. L. Powell (Invited Presentation)

"Initial Calorimetry Experiments in the Physics Division -- ORNL"

42nd Annual Gaseous Electronics Conference, Palo Alto, California, October 17-20, 1989

Phaneuf, R. A.

"Atomic Collision Processes in the Edge Plasma of Magnetic Fusion Devices"

Symposium on the Nucleus at High Spin (Mainly): Nuclear Structure in the Era of New Spectroscopy, Copenhagen, Denmark, October 19-24, 1989

Raman, S.

"Systematics of Low-Lying Quadrupole and Octupole Strengths in Even-Even Nuclei"

Symposium of Northeastern Accelerator Personnel (SNEAP '89), Oak Ridge, Tennessee, October 23-26, 1989

Haynes, D. L., and C. M. Jones

"Holifield Facility Tandem Accelerator Auxiliary Gas-Containment Valves"

Jones, C. M., D. L. Haynes, R. C. Juras, M. J. Meigs, and N. F. Ziegler

"Operational Experience with Compressed Geometry Acceleration Tubes in the Oak Ridge 25URC Tandem"

Jones, N. (Invited Presentation)

"A Repair of a Charging Belt"

Olsen, D. K.

"Introduction to ECR Sources in Electrostatic Machines"

Fifth International Symposium on the Production and Neutralization of Negative Ion Beams, Upton, New York, October 30, 1989

Alton, G. D.

"Design Features of an Axial-Geometry, Plasma-Sputter, Heavy Negative Ion Source"

Annual Meeting of the Southeastern Section of the American Physical Society, Tuscaloosa, Alabama, November 9-11, 1989

Hamilton, W. D., W. L. Croft, J. C. Morgan, G. B. Quinn, J. M. Turner, W. H. Brantley, C. D. Roper, M. Veskovic, and H. K. Carter

"Preparation of Nuclear Orientation Sources by Recoil Ion Implantation," Bull. Am. Phys. Soc. 34, 2361 (Nov. 1989)

Johnson, N. R. (Invited Presentation)

"Nuclear Rotational States -- Experimental Lifetimes and Matrix Elements," Bull. Am. Phys. Soc. 34, 2367 (Nov. 1989)

Stelson, P. H.

"Analysis of Fusion Cross Section for $^{16,17,18}\text{O}$ on Sn Isotopes," Bull. Am. Phys. Soc. 34, 2361 (Nov 1989)

Zhao, X., L. Chaurvedi, J. H. Hamilton, A. V. Ramayya, J. Kornicki, S. J. Zhu, C. Girit, W. B. Gao, Y. Jiang, H. Xie, N. R. Johnson, I. Y. Lee, C. Baktash, F. K. McGowan, M. L. Halbert, M. O. Kortelahti, and J. D. Cole

"Contrasting Level Structures of ^{68}Ge and ^{72}Se ," Bull. Am. Phys. Soc. 34, 2361 (Nov. 1989)

American Physical Society, Division of Plasma Physics, Anaheim, California, November 13-17, 1989

Ma, C. H., C. A. Bennett, D. P. Hutchinson, and K. L. Vander Sluis

"FIR Interferometer and Scattering Measurements on ATF," Bull. Am. Phys. Soc. 34, 1947 (Oct. 1989)

Symposium on Laser-Aided Plasma Diagnostics, Kyushu University, Fukuoka, Japan, November 20-23, 1989

Richards, R. K. (Invited Presentation)

"Alpha Particle Measurement by CO_2 Laser Thomson Scattering"

Winter School on Quark-Gluon Plasma, Puri, Orissa, India, December 5-16, 1989

Close, F. E. (Invited Presentation)

"Quarks and Gluons in Hadrons and Nuclei"

1989 International Chemical Congress of Pacific Basin Societies, Honolulu, Hawaii, December 17-22, 1989

Nitschke, J. M., P. A. Wilmarth, and K. S. Toth

"Beta-Delayed Proton Decay in the Lanthanide Region"

1990

American Physical Society, Division of Particles and Fields, Houston, Texas, January 3-6, 1990

Young, G. R. (Invited Presentation)

"Experimental Results from Studies of Nucleus-Nucleus Collisions at High Energy"

XIII Symposium on Nuclear Physics, Oaxtepec, Mexico, January 3-6, 1990

Gomez del Campo, J. (Invited Presentation)

"Populations of Excited States and Reaction Mechanisms in the Emission of Complex Fragments"

Gross, E. E. (Invited Presentation)

"Heavy Ion Inelastic Scattering with a 4π Gamma Detector"

International Workshop XVIII on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 15-20, 1990

Awes, T. C.

"Two-Proton Correlations as Predicted by Landau-Vlasov Calculations"

Nuclear Microprobe Technology and Applications, Melbourne, Australia, February 5-9, 1990

Alton, G. D., and P. M. Read

"The Emittance and Brightness Characteristics of Ga and Li Needle-Type Liquid-Metal Ion Sources"

International Workshop on Polarized Ion Sources and Gas Jets, Tsukuba, Japan, February 12-19, 1990

Alton, G. D. (Invited Presentation)

"Negative Ion Formation Processes: A General Review"

Second International Conference on Nuclear Microprobe Technology and Applications, Melbourne, Australia, February 5-9, 1990

Alton, G. D., and P. M. Read

"The Emittance and Brightness Characteristics of Ga and Li Needle-Type Liquid-Metal-Ion Sources"

VI International Workshop on Nuclear Dynamics, Jackson Hole, Wyoming, February 19-23, 1990

Plasil, F., Albrecht, R., T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. J. Lee, H. Lochner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, A. M. Poskanzer, M. Purschke, H. G. Ritter, S. Saini, R. Santo, H. R. Schmidt, T. Siemiarczuk, S. P. Sorensen, K. Steffens, E. Stenlund, D. Stucken, M. L. Tincknell, and G. R. Young

"Nuclear Collisions at 200 GeV/Nucleon from WA80 Experiment at CERN"

Workshop on Heavy-Ion Physics at the AGS, Upton, New York, March 5, 1990

Young, G. R. (Invited Presentation)

"Experimental Results Concerning Global Observables from the CERN SPS Heavy Ion Program"

Proceedings, International Workshop on Software Engineering, Artificial Intelligence and Expert Systems for High Energy and Nuclear Physics, Lyon, France, March 19-24, 1990

Awes, T. C. (Invited Presentation)

"A Neural-Network Approach to the Problem of Photon-Pair Combinatorics"

First Annual Cold Fusion Conference, Salt Lake City, Utah, March 27-30, 1990

Hutchinson, D. P., C. A. Bennett, R. K. Richards, J. Bullock IV, and G. L. Powell (Invited Presentation)

"Initial Calorimetry Experiments in the Physics Division - ORNL"

American Physical Society Meeting, Washington, D. C., April 16-19, 1990

Bingham, C. R. M. B. Kassim, M. Zhang, W. D. Hamilton, Y. A. Akovali, K. S. Toth, H. K. Carter, L.A. Rayburn, J. Schwarzenberg, M. M. Jarrio, and J. Kormicki

"Alpha Decay of Mass-Separated ^{181}Au ," Bull. Am. Phys. Soc. 35, 1016 (Apr. 1990)

Carmichael, H. V., C. R. Bingham, L. L. Riedinger, P. B. Semmes, H. K. Carter, E. F. Zganjar, M. O. Kortelahi, and J. L. Wood

"Decay of Mass-Separated ^{193}Tl : Interpretation Based on a Particle-Core Coupling Model," Bull. Am. Phys. Soc. 35, 1016 (Apr. 1990)

Garrett, J. D., J. M. Espino, L. Courtney, and C.-H. Yu

"Is the Structure of Rapidly Rotating Cold Nuclei Ordered or Chaotic?," Bull. Am. Phys. Soc. 35, 997 (Apr. 1990)

Gross, E. E., D. C. Hensley, J. R. Beene, F. E. Bertrand, M. L. Halbert, G. Vourvopoulos, and D. L. Humphrey

"Particle- γ Correlation Determination of Static Quadrupole Moments," Bull. Am. Phys. Soc. 35, 1059 (Apr. 1990)

Jin, H. Q., B. Edington, L. L. Riedinger, C.-H. Yu, L. Zhou, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, F. K. McGowan, H. Xie, and L. Chaturvedi

"Rotational Band Structures in ^{175}Re ," Bull. Am. Phys. Soc. 35, 1015 (Apr. 1990)

Kassim, M. B., C. R. Bingham, M. Zhang, W. D. Hamilton, Y. A. Akovali, K. S. Toth, H. K. Carter, J. Schwarzenberg, M. M. Jarrio, and J. Kormicki

"Alpha Decay of Mass-Separated $^{182-186}\text{Au}$," Bull. Am. Phys. Soc. 35, 1016 (Apr. 1990)

Liu, X. T., M. W. Guidry, S. P. Sorensen, R. W. Kincaid, X. L. Han, D. Cline, C. Y. Wu, W. J. Kernan, T. Czosnyka, A. E. Kavka, M. L. Halbert, I. Y. Lee, and C. Baktash

"Rotational Signatures for Population of High-Spin States in Transfer Reactions," Bull. Am. Phys. Soc. 35, 997 (Apr. 1990)

McNeill, J. H., C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, F. K. McGowan, H. Xie, C.-H. Yu, and L. L. Riedinger

"High-Spin Studies of the Odd-Odd Nucleus ^{166}Lu ," Bull. Am. Phys. Soc. 35, 997 (Apr. 1990)

Pilotte, A., H. Q. Jin, J. Lewis, X. T. Liu, L. L. Riedinger, C.-H. Yu, L. Zhou, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, F. K. McGowan, J. McNeill, M. P. Carpenter, and R.V.F. Janssens
 "Band Structures in ^{191}Tl ," Bull. Am. Phys. Soc. 35, 1016 (Apr. 1990)

Stelson, P. H. (Invited Presentation)

"Intimations of Neck Formation in Heavy-Ion Subbarrier Fusion Reactions," Bull. Am. Phys. Soc. 35, 1011 (Apr. 1990)

Xie, H., F. K. McGowan, N. R. Johnson, J. D. Garrett, C. Baktash, I. Y. Lee, C.-H. Yu, J. C. Wells, J. H. Hamilton, and A. V. Ramayya

"High Spin Lifetimes in ^{164}Yb ," Bull. Am. Phys. Soc. 35, 997 (Apr. 1990)

Yu, C.-H., H. Q. Jin, J. Lewis, L. L. Riedinger, L. Zhou, C. Baktash, J. D. Garrett, I. R. Jiant, N. Johnson, I. Y. Lee, F. McGowan, J. H. McNeill, H. Xie, and L. Chaturvedi

"High Spin Studies in the Odd-Odd Nucleus ^{180}Ir ," Bull. Am. Phys. Soc. 35, 1015 (Apr. 1990)

Conference on Nuclear Structure in the Nineties, Oak Ridge, Tennessee, April 23-27, 1990

Baktash, C., G. Garcia-Bermudez, M. L. Halbert, D. C. Hensley, N. R. Johnson, I. Y. Lee, F. K. McGowan, M. A. Riley, A. Virtanen, V. Abenante, D. G. Sarantites, T. M. Semkow, H. C. Griffin, and W. Nazarewicz

"Shape Coexistence and Disappearance of Pairing Correlations in ^{82}Sr "

Baktash, M. L. Halbert, D. C. Hensley, N. R. Johnson, I. Y. Lee, J. W. McConnell, and F. K. McGowan

"Study of Spin-Temperature Effects Using Energy-Ordered Continuum Gamma-Ray Spectroscopy Technique"

Bertrand, F. E., and J. R. Beene (Invited Presentation)

"Excitation and Photon Decay of Giant Multipole Resonances"

Cardona, M. A., G. Garcia-Bermudez, C. Baktash, M. L. Halbert, D. C. Hensley, N. R. Johnson, I. Y. Lee, F. K. McGowan, M. A. Riley, A. Virtanen, V. Abenante, D. G. Sarantites, T. M. Semkow, and H. C. Griffin

"High Spin States in ^{80}Rb "

Espino, J. M., J. D. Garrett, J. Nyberg, and J. H. McNeill

"The Stability of Nuclear Shape Correlations"

Garrett, J. D., and J. M. Espino

"Is the Structure of Rapidly-Rotating Cold Nuclei Ordered or Chaotic?"

Garrett, J. D., J. M. Espino, and J. Nyberg

"The Stability of Nuclear Pair Correlations"

Garrett, J. D., J.-Y. Zhang, C.-H. Yu, and M. Carpenter

"The Rare Earth Region in Gauge Space"

Lee, I. Y. (Invited Presentation)

"The Gammasphere"

Lee, I. Y., C.-H. Yu, J. D. Garrett, and J. H. McNeill

"Coulomb Excitation of ^{159}Tb with ^{208}Pb "

Nicolis, N. G., D. G. Sarantites, C. Baktash, V. Abenante, L. A. Adler, J. R. Beene, F. A. Dilmanian, G. Garcia-Bermudez, H. C. Griffin, M. L. Halbert, D. C. Hensley, N. R. Johnson, I. Y. Lee, Z. Majka, F. K. McGowan, M. A. Riley, T. M. Semkow, D. W. Stracener, and A. Virtanen (Invited Presentation)

"Alpha-Particle Emission as a Probe of Nuclear Shapes and Structure in Proton Evaporation Spectra"

Toth, K. S., D. C. Sousa, J. M. Nitschke, K. S. Vierinen, and P. A. Wilmarth

"Single-Particle States Near the Proton Drip Line"

Xie, H., J. D. Garrett, F. K. McGowan, R. Wyss, C.-H. Yu, N. R. Johnson, I. Y. Lee, C. Baktash, and J. H. Hamilton

"High-Spin Losses of Collectivity in the Ytterbium Isotopes"

Xie, H., F. K. McGowan, C.-H. Yu, N. R. Johnson, J. D. Garrett, C. Baktash, I. Y. Lee, J. C. Wells, J. H. Hamilton, A. V. Ramayya, and L. L. Reidinger

"The High Spin Collectivity of ^{164}Yb "

Yu, C.-H., J. D. Garrett, G. B. Hagemann, and J. Gascon

"The Shape Polarization of Odd-Z Orbitals in Rare Earth Nuclei"

Yu, C.-H., H.-Q. Jin, J. Lewis, L. L. Reidinger, L. Zhou, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, F. K. McGowan, J. H. McNeill, L. Chaturvedi, Y. R. Jiang, and H. Xie

"High Spin Studies in the Odd-Odd Nucleus ^{180}Ir "

Zhang, J. Y., J. D. Garrett, R. F. Casten, D. S. Brenner, C. Wesselborg, C.-H. Yu, and M. Carpenter (Invited Presentation)

"Empirical Estimates of the Proton-Neutron Interaction and Diaboloical Points"

Zhang, J. Y., J. D. Garrett, C.-S. Wu, and C.-H. Yu

"A New Technique for Obtaining Empirical Proton-Neutron Interactions"

XXV Zakopane School of Physics, Zakopane, Poland, May 5-12, 1990

Sarantites, D. G., N. G. Nicolis, V. Abenante, Z. Majka, T. M. Semkow, C. Baktash, J. R. Beene, G. Garcia-Bermudez, M. L. Halbert, D. C. Hensley, N. R. Johnson, I. Y. Lee, F. K. McGowan, M. A. Riley, A. Virtanen, and H. C. Griffin

"Alpha-Particles as Probes of Nuclear Shape and Structure Effects in Proton Evaporation Spectra"

Eighth Topical Conference on High-Temperature Plasma Diagnostics, Hyannis, Massachusetts, May 6-10, 1990

Hutchinson, D. P., R. K. Richards, H. T. Hunter, and C. A. Bennett

"A Proof of Principle Test of a Thomson Scattering Alpha Particle Diagnostic"

Ma, C. H., D. P. Hutchinson, and K. L. Vander Sluis

"A Difluoromethane Laser Interferometer System on ATF"

Interaction of Charged Particles with Solids and Surfaces, Alicante, Spain, May 6-18, 1990

Burgdorfer, J. (Invited Presentation)

"Convoy Electrons"

Workshop on Network Security, Augusta, Georgia, May 7-10, 1990

Bemis, C. E., Jr. (Invited Presentation)

"Aspects of Network Security in Large Global DECnet Networks"

Second International Conference on Medium- and High-Energy Nuclear Physics, Taiwan, Republic of China, May 8-12, 1990

Wu, J. S., C. Boucher, M. R. Strayer, D. J. Ernst, and A. K. Kerman

"Coherent Particle Production from Relativistic Heavy-Ion Collisions"

Albert, C. J., D. J. Ernst, C. Boucher, and M. R. Strayer (Invited Presentation)

"Spin Effects in Two-Proton Pair Production"

American Physical Society, Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, Monterey, California, May 21-23, 1990

Benhenni, M., S. M. Shafroth, J. K. Swenson, H. Schone, C. J. Gaither, C. R. Vane, P. F. Dittner, S. Datz, M. Schulz, J. P. Giese, and T. J. M. Zouros

"Angular Distribution of Auger Electrons Emitted from the Decay of the Metastable State $(1s2s2p)^4P$ at 8 and 6 MeV O^{5+} on He Collisions," Bull. Am. Phys. Soc. 35, 1149 (May 1990)

Biedermann, C., H. Cederquist, L. R. Anderson, J. C. Levin, R. T. Short, S. B. Elston, J. P. Gibbons, H. Andersson, L. Liljeby, and I. A. Sellin

"One- and Two-Electron Processes on Very Slow Ar^{4+} - Ar Collisions," Bull. Am. Phys. Soc. 35, 1180 (May 1990)

Bottrell, G. J., C. Boucher, and M. R. Strayer

"Time Dependent Hartree-Fock Calculations of Ion-Atom Collisions: $p+H^+$," Bull. Am. Phys. Soc. 35, 1200 (May 1990)

Burgdorfer, J. (Invited Presentation)

"Fast Antiproton Interaction in Condensed Matter," Bull. Am. Phys. Soc. 35, 1185 (May 1990)

Dittner, P. F., S. Datz, R. Vane, H. F. Krause, J. Gomez del Campo, R. Watson, P. Zeijlmans van Emmichoven, and U. Bechthold

"Resonant Dielectronic Excitation of Ti Ions in A Crystal Channel," Bull. Am. Phys. Soc. 35, 1160 (May 1990)

Gaither, C. C., III, M. Breinig, and T. A. Underwood

"Cusp/Convoy and Rydberg Electrons from Ion-Atom and Ion-Solid Collisions," Bull. Am. Phys. Soc. 35, 1145 (May 1990)

Levin, J. E., R. T. Short, C. Biedermann, N. Keller, L. Liljeby, D. Lindle, and I. A. Sellin

"Coincidence Measurements of Argon Ions with Auger Electrons Following K-Shell Photoionization with Synchrotron Radiation," Bull. Am. Phys. Soc. 35, 1187 (May 1990)

Meyer, F. W., C. C. Havener, and P. A. Zeijlmans van Emmichoven

"Electron Spectroscopic Studies of the Neutralization of Slow Multicharged Ions Close to Metal Surfaces," Bull. Am. Phys. Soc. 35, 1200 (May 1990)

Pindzola, M. S., G. J. Bottchell, and C. R. Bottcher

"Multiphoton Ionization of Atoms Using Time Dependent Hartree-Fock Methods," *Bull. Am. Phys. Soc.* **35**, 1151 (May 1990)

Shafroth, S. M., M. Benhenni, T. Zouros, P. F. Dittner, H. F. Krause, H. Schone, C. R. Vane, L. D.

Hendrick, J. M. Anthony, Q. Kessell, E. Devony, and C. J. Gaither

"Projectile Electron Spectra and Angular Distributions for 13 MeV O^{5+} on H^2 ," *Bull. Am. Phys. Soc.* **35**, 1144 (May 1990)

Underwood, T. A., M. Breinig, and C. C. Gaither III

"Formation of Projectile Excited States Near the Double Escape Threshold," *Bull. Am. Phys. Soc.* **35**, 1180 (May 1990)

Vane, C. R., S. Datz, P. F. Dittner, H. F. Krause, T. M. Rosseel, and R. S. Patterson

"X-Rays from H-Like Calcium Ions Excited in Channels of α Si-1100 Single Crystal," *Bull. Am. Phys. Soc.* **35**, 1160 (May 1990)

Wang, J., and J. Burgdorfer

"Enhancement of Electron Loss Cross Section at Backward Angles by Second-Order Processes," *Bull. Am. Phys. Soc.* **35**, 1150 (May 1990)

Third International Spring Seminar on Nuclear Physics, "Understanding the Variety of Nuclear Excitations," Ischia, Italy, May 21-25, 1990

Beene, J. R. and F. E. Bertrand (Invited Presentation)

"Giant Resonance Decay"

Workshop on the Interface Between Nuclear Structure and Heavy-Ion Reaction Dynamics, Notre Dame, Indiana, May 24-26, 1990

Bertrand, F. E., and J. R. Beene (Invited Presentation)

"Photon Decay of Giant Multipole Resonances"

Gross, E. E., D. C. Hensley, J. R. Beene, F. E. Bertrand, M. L. Halbert, G. Vourvopoulos, and D. L. Humphrey

"Particle- γ Correlation Determination of Static Quadrupole Moments"

Kim, H. J., J. Gomez del Campo, D. Shapira, and P. H. Stelson

"Multinucleon Transfer Reactions for the $^{50}Ti + ^{93}Nb$ Reaction at Sub- and Near-Barrier Energies"

Ray, A., D. Shapira, M. L. Halbert, J. Gomez del Campo, H. J. Kim, J. P. Sullivan, B. Shivakumar, and J. Mitchell

"Spin Alignment and Density Matrix Measurement in $^{28}Si + ^{12}C$ Orbiting Reaction"

Thoennessen, N., J. R. Beene, R. L. Auble, F. E. Bertrand, C. Baklash, M. L. Halbert, D. J. Horen, C. A. Ludemann, D. G. Sarantites, D. W. Stracener, and W. Spang

"Observation of Entrance Channel Effects in Compound Nucleus Formation with High Energy γ -Rays"

Miniworkshop on Quantum Chaos, Treiste, Italy, June 4-July 6, 1990

Muller, J., J. Burgdorfer, and D. W. Noid

"Semiclassical Eigenenergies in the Wake of Fast Ions in Solids"

Yang, X., J. Burgdorfer, E. Eschenazi

"On the Morphology of Avoided Crossings in the Spectrum of Irregular Quantum Systems"

Second European Particle Accelerator Conference, Acropolis, Nice, France, June 12-16, 1990

Alton, G. D.

"Design Considerations for a Pulsed-Mode, High-Intensity, Heavy Negative Ion Source"

Olsen, D. K., G. D. Alton, D. T. Dowling, D. L. Haynes, C. M. Jones, R. C. Juras, S. N. Lane, M. J. Meigs, G. D. Mills, S. W. Mosko, and B. A. Tatum

"Recent Developments at the HHIRF"

International Conference on Particles and Nuclei (PANIC XIII), Cambridge, Massachusetts, June 25-29, 1990

Baghaei, H., A. Cichocki, J. B. Flanz, M. Frodyma, B. Frois, Y. Han, R. S. Hicks, J. Martino, R. A. Miskimen, C. N. Papanicolas, G. A. Peterson, S. Platchkov, S. Raman, S. H. Rokni, and T. Suzuki

"Elastic Magnetic Electron Scattering from ^{41}Ca "

Kumano, S., and F. E. Close

"Local EMC Effects"

Sorensen, S. P.

"Experimental Results from CERN on Reaction Mechanisms in High-Energy Heavy-Ion Collisions"

Conference on Particle Correlations and Interferometry in Nuclear Collisions, Nantes, France, June 28-30, 1990

Korolija, M., D. Shapira, J. Gomez del Campo, H. J. Kim, K. Teh, J. Y. Shea, J. P. Wieleczko, and N. Cindro

"Two-Proton Correlations from the $^{58}\text{Ni} + ^{58}\text{Ni}$ Reaction at $E_{\text{inc}} = 876.5 \text{ MeV}$ "

15th International Conference on X-Ray and Inner-Shell Processes, Knoxville, Tennessee, July 9-13, 1990

Becker, R. L., L. Vegh, and J. H. Macek

"Reflection Symmetry and Angular Correlations of Autoionization Electrons"

Dellwo, J., D. J. Pegg, J. S. Thompson, and G. D. Alton

"A New Method for Measuring Electron Affinities"

Workshop on Heavy-Ion Collisions at Energies Near the Coulomb Barrier, Daresbury, England, July 5-7, 1990

Sachler, G. R. (Invited Presentation)

"Comments on the Current Status and Possible Future Directions of Research on Heavy-Ion Interactions Near the Coulomb Barrier"

15th International Conference on X-Ray and Inner-Shell Processes (X-90), Knoxville, Tennessee, July 9-13, 1990

Swenson, J. K., J. Burgdorfer, C. C. Havener, D. C. Gregory, N. Stolterfoht, and F. W. Meyer
 "Coulomb Focussing and Interference of Autoionization Electrons Produced in Slow $\text{He}^+ + \text{He}$ Collisions"

Vegh, L., and R. L. Becker
 "Angular Correlation of an Auger Electron with a Photoelectron in the Direction of Linear Polarization"

Vegh, L., R. L. Becker, and J. H. Macek
 "Exchange Effect on the Angular Correlation Between Directly Ionized and Autoionized Electrons of the Same Energy"

25th International Conference on High Energy Physics, Singapore, Republic of Singapore, August 2-8, 1990

Plasil, F., R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, A. M. Poskanzer, M. Purschke, H. G. Ritter, S. Saini, R. Santo, H. R. Schmidt, T. Siemiarz, S. P. Sorensen, K. Steffens, E. Stenlund, D. Sueken, M. L. Tincknell, and G. R. Young
 "Nucleus-Nucleus Collisions at 60 to 200 GeV/Nucleon: Results from the WA80 Experiment at CERN"

Fourth Asia Pacific Physics Conference, Seoul, Korea, August 13-17, 1990

Kim, H. J., J. Gomez del Campo, D. Shapira, and P. H. Stelson
 "Liquid-Drop Effects in Subbarrier Heavy-Ion Reactions"

Workshop on Soft Lepton Pair and Photon Production, Pittsburgh, Pennsylvania, September 6-8, 1990

Woody, C., D. Lissauer, J. Gomez del Campo, A. Ray, D. Shapira, M. Tincknell, R. Clark, C. Erd, J. Schurkraft, and W. Willis
 "Status of Soft Photons in Experiment E855"

8th International Conference on Atomic Masses and Fundamental Constants (AMCO-8), Jerusalem, Israel, September 9-14, 1990

Bingham, C. R., M. B. Kassim, M. Zhang, Y. A. Akovali, K. S. Toth, W. D. Hamilton, H. K. Carter, J. Kormicki, J. Schwarzenberg, and M. M. Jarrio
 "New Mass Differences and α -Decay Rates for Au and Pt Isotopes"

Raman, S. (Invited Presentation)
 "Low-Lying Collective Quadrupole and Octupole Strengths in Even-Even Nuclei"

Toth, K.S., D. M. Moliz, and J. D. Robertson
 "Masses and α -Decay Rates of Proton-Rich Lead Isotopes"

Toth, K.S., J. M. Nitschke, K. S. Vienninen, and P. A. Wilmarth
 "Excitation Energies of $h_{11/2}$ and $s_{1/2}$ Proton States in Rare Earth Nuclei"

Vth International Conference on the Physics of Highly Charged Ions, Giessen, West Germany, September 10-14, 1990

Datz, S., P. F. DiTune, J. Gomez del Campo, H. F. Krause, T. M. Rossell, and C. R. Vane (Invited Presentation)

"Electron Ion Interactions in Crystal Channels: Collisions in Ultra-Dense Electron Media"

Havener, C. C., and R. A. Phaneuf (Invited Presentation)

"Electron Capture in Slow Collisions of Multicharged Ions with Hydrogen Atoms Using Merged Beams"

Wahlin, E. K., J. S. Thompson, G. H. Dunn, R. A. Phaneuf, D. C. Gregory, and A.C.H. Smith

"Electron Impact Excitation, $e + \text{Si}^{3+}(^2\text{S}_{1/2}) \rightarrow e + \text{Si}^{3+}(^2\text{P}_{1/2,3/2})$, Using Electron Energy Loss in Merged Beams"

Workshop on Fast Ion Collisions, Debrecen, Hungary, September 17-19, 1990

Burgdorfer, J. (Invited Presentation)

"Electronic Excitations in Fast Ion-Solid Collisions"

Elston, S. B. (Invited Presentation)

"The Development of Projectile Excitation During Ion-Solid Collisions Observed Through Convoy Electron Emission"

Sellin, I. A. (Invited Presentation)

"Newly Appreciated Roles for Electrons in Ion-Atom Collisions"

International Conference on High-Spin Physics and Gamma-Soft Nuclei, Pittsburgh, Pennsylvania, September 17-21, 1990

Baktash, C., M. L. Halbert, D. C. Hensley, N. R. Johnson, I. Y. Lee, J. W. McConnell, and F. K. McGowan

"Study of Spin-Temperature Effects Using Energy-Ordered Continuum Gamma-Ray Spectroscopy Technique"

Bengtsson, R.

"The Importance of Triaxial Shapes in Spin Aligned Configurations in the $A = 170$ -180 Mass Region"

Gao, W. B., I. Y. Lee, C. Baktash, J. Beene, J. D. Garrett, J. H. Hamilton, N. R. Johnson, F. K. McGowan, and H. Xie

"Rotational Damping Width from a Triple E_γ Correlation Study of ^{130}Ce "

Garrett, J. D., C. Baktash, C.-H. Yu, and W. Nazarewicz

"Identical" Rotational Bands in Normally Deformed Nuclei

Lee, I. Y.

"Lifetimes in the Continuum"

Wyss, R., and A. Johnson

"Unexpected Alignment Patterns in High-J Intruder Bands; Evidence for a Strong Residual Neutron Proton Interaction?"

Xie, H., J. D. Garrett, C. Baktash, J. H. Hamilton, N. R. Johnson, I. Y. Lee, F. K. McGowan, J. C. Wells, and C.-H. Yu

"Enhanced $B(E1)/B(E2)$ Ratios in ^{164}Yb and the Octupole Stability"

Yu, C.-H., H. Q. Jin, L. L. Riedinger, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, and F. McGowan
"Signature Inversion of Transition Rates in ^{180}Ir "

Yu, C.-H., F. K. McGowan, I. Y. Lee, J. D. Garrett, W. B. Gao, H. Q. Jin, N. R. Johnson, J. Lewis,
S. Pilotte, L. L. Riedinger, J. C. Wells, and H. Xie
"High-Spin Lifetimes in ^{161}Lu "

**Meeting of the IAEA Coordinated Research Programme on "Atomic and Molecular Data
for Fusion Edge Plasmas," Vienna, Austria, September 24-26, 1990**

Phaneuf, R. A. (Invited Presentation)

"Assessment of Ion-Atom Collision Data for Magnetic Fusion Plasma Edge Modelling"

**Workshop on Low- and Medium-Energy Heavy-Ion Reactions, Kyoto, Japan, September
27-29, 1990**

Kim, H. J. (Invited Presentation)

"Reactions Between Medium-Mass Nuclei at Subbarrier Energies"

12. GENERAL INFORMATION

PERSONNEL CHANGES

New Staff Members

F. E. Barnes, University of Toronto, Toronto, Canada
B. R. Bengtsson, Oak Ridge Associated Universities, Oak Ridge, Tennessee (UNISOR)

Staff Assignments

S. Datz, on 12-month assignment at Manne Siegbahn Institute of Physics, Stockholm, Sweden,
as Tage Erlander National Science Professor
H. J. Kim, on 12-month assignment at Japan Atomic Energy Research Institute, Tokai-mura,
Ibaraki-ken, Japan

Staff Transfers and Terminations

A. Scientific Staff

E. C. Halbert (retirement)
H. T. Hunter (transferred to Engineering Physics and Mathematics Division)
C. A. Ludemann (transferred to Human Resources Division)
N. F. Ziegler (retirement)

B. Administrative and Technical Staff

B. K. Sizemore, Accelerator Operations (transferred to Quality Division)
S. D. Taylor, Accelerator Operations (transferred to Environmental and Health Protection Division)

Temporary Assignments

A. Visiting Scientists

W. L. Croft, Mississippi State University, Mississippi State, Mississippi
R. DeSerio, University of Tennessee, Knoxville, Tennessee
X-L. Han, University of Tennessee, Knoxville, Tennessee, and Jilin University, Changchun,
People's Republic of China
K. Kimura, Kyoto University, Kyoto, Japan
J. Kormicki, Vanderbilt University, Nashville, Tennessee
J. S. Thompson, Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder,
Colorado
R. Wang, University of Science and Technology, Hefei, Anhui, People's Republic of China
R. L. Watson, Texas A&M University, College Station, Texas
J. Wu, University of Tennessee, Knoxville, Tennessee
L. Zhou, University of Tennessee, Knoxville, Tennessee, and Institute of Atomic Energy, Beijing,
People's Republic of China

B. Postdoctoral Research Associates

E. Chavez-Lomeli, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico
 A. Franz, University of Tennessee, Knoxville, Tennessee
 J. Kemmler, University of Tennessee, Knoxville, Tennessee
 M. D. Kovarik, University of Tennessee, Knoxville, Tennessee
 J. C. Levin, University of Tennessee, Knoxville, Tennessee
 Z-P. Li, University of Tennessee, Knoxville, Tennessee
 W-c. Ma, Vanderbilt University, Nashville, Tennessee
 P. F. Mantica, Jr., Oak Ridge Associated Universities (UNISOR), Oak Ridge, Tennessee
 J. H. McNeill, University of Manchester, Manchester, United Kingdom
 R. D. Miller, University of Tennessee, Knoxville, Tennessee
 S. Pilotte, University of Tennessee, Knoxville, Tennessee
 A. Ray, University of Tennessee, Knoxville, Tennessee
 C. O. Reinhold-Larsson, University of Tennessee, Knoxville, Tennessee
 S. Saini, University of Tennessee, Knoxville, Tennessee
 M. R. Thoennessen, University of Tennessee, Knoxville, Tennessee
 U. Thumm, Freiburg University, Freiburg, Germany
 M. L. Tinknell, University of Tennessee, Knoxville, Tennessee
 J. D. Weinstein, University of Tennessee, Knoxville, Tennessee
 J. P. Wieleczko, Commissariat a l'Energie Atomique, Gif-sur-Yvette Cedex, France
 C-H. Yu, University of Tennessee, Knoxville, Tennessee
 P. Zeijlmans van Emmichoven, Rijksuniversiteit te Utrecht, Utrecht, the Netherlands

C. Graduate Students

U. Bechthold, University of Frankfurt, Frankfurt, Germany
 J. W. Berryman, University of Tennessee, Knoxville, Tennessee
 C. Biedermann, University of Frankfurt, Frankfurt, Germany
 H. V. Carmichael, University of Tennessee, Knoxville, Tennessee
 R. L. Clark, Vanderbilt University, Nashville, Tennessee
 D. J. Dean, Vanderbilt University, Nashville, Tennessee
 J. Dellwo, University of Tennessee, Knoxville, Tennessee
 J-K. Deng, Vanderbilt University, Nashville, Tennessee
 J. E. Freyou, University of Tennessee, Knoxville, Tennessee
 C. C. Gaither, University of Tennessee, Knoxville, Tennessee
 W-B. Gao, Vanderbilt University, Nashville, Tennessee
 J. P. Gibbons, University of Tennessee, Knoxville, Tennessee
 P. M. Gore, University of Tennessee, Knoxville, Tennessee
 G. R. J. Grondin, University of Toronto, Toronto, Canada
 B. F. Hasson, University of Tennessee, Knoxville, Tennessee
 R. C. Hunt, University of Tennessee, Knoxville, Tennessee
 Y-r. Jiang, Vanderbilt University, Nashville, Tennessee
 H. Jin, University of Tennessee, Knoxville, Tennessee
 E. F. Jones, Vanderbilt University, Nashville, Tennessee
 M-s. B. Kassim, University of Tennessee, Knoxville, Tennessee
 N. Keller, University of Tennessee, Knoxville, Tennessee
 R. W. Kincaid, University of Tennessee, Knoxville, Tennessee
 M. Korolija, Ruder Boskovic Institute, Croatia, Yugoslavia
 J. G. Kreke, University of Tennessee, Knoxville, Tennessee
 T. S. Lam, Louisiana State University, Baton Rouge, Louisiana
 J. M. Lewis, Jr., University of Tennessee, Knoxville, Tennessee
 J. Mueller, University of Frankfurt, Frankfurt, Germany
 J. D. Richards, University of Tennessee, Knoxville, Tennessee
 H. Schone, University of Frankfurt, Frankfurt, Germany

C. Graduate Students (continued)

W. Spang, KFA Julich, Germany
 T. A. Underwood, University of Tennessee, Knoxville, Tennessee
 J. Wang, University of Tennessee, Knoxville, Tennessee
 Y-s. Xu, Oregon State University, Corvallis, Oregon
 H. Xie, Vanderbilt University, Nashville, Tennessee
 X. Yang, University of Tennessee, Knoxville, Tennessee
 M. Zhang, University of Tennessee, Knoxville, Tennessee

D. Joint Institute for Heavy Ion Research (JHIR) Long-Term Guests

Y. S. Chen, Institute of Atomic Energy, Beijing, People's Republic of China
 Y. Liu, University of Tennessee, Knoxville, Tennessee
 C-L. Wu, Jilin University, Changchun, People's Republic of China
 R. A. Wyss, Royal Institute of Technology, Stockholm, Sweden
 J. Y. Zhang, Lanzhou University, Lanzhou, People's Republic of China

E. ORAU Laboratory Co-op Faculty Research Participant

H. A. Schuessler, Texas A&M University, College Station, Texas

F. ORAU Laboratory Graduate Research Participant

J. Y. Shea, Vanderbilt University, Nashville, Tennessee

G. ORAU Student Research Participant

A. J. Mason, Western Kentucky University, Bowling Green, Kentucky

H. Oak Ridge Science and Engineering Research Semester (ORSERS) Participants

J. R. German, Winona State University, Winona, Minnesota
 S. M. King, North Georgia College, Dahlonega, Georgia
 M. M. Messick, Gettysburg College, Gettysburg, Pennsylvania
 J. K. Pope, University of North Carolina, Charlotte, North Carolina
 L. Y. Shen, University of Miami, Miami, Florida
 E. D. Thoma, University of North Carolina, Asheville, North Carolina
 R. C. Whaley, Oklahoma Panhandle State University, Goodwell, Oklahoma

I. Great Lakes Colleges Association Science Program Participants

S. R. Broshar, Lawrence University, Appleton, Wisconsin
 W. A. Franklin, Carleton College, Northfield, Minnesota
 K. M. Isbister, DePauw University, Greencastle, Indiana
 V. A. Magrotta, Albion College, Albion, Michigan
 P. L. Mikelsons, Macalester College, St. Paul, Minnesota

J. Individual Student Research Participants

R. J. Barb, University of Tennessee, Knoxville, Tennessee
 C. D. Barber, University of Tennessee, Knoxville, Tennessee
 S. A. Bowling, University of Tennessee, Knoxville, Tennessee
 J. C. Leonard, Berea College, Berea, Kentucky
 M-B. Liu, University of Tennessee, Knoxville, Tennessee
 O. E. Messer, University of Tennessee, Knoxville, Tennessee
 Y. Zhang, University of Tennessee, Knoxville, Tennessee

K. Special High School Honors Program Participant

D. W. Cofer, Oliver Springs High School, Oliver Springs, Tennessee

Summer Assignments**A. ORAU Faculty Research Participant**

J. C. Wells, Tennessee Technological University, Cookeville, Tennessee

B. HBCU/Faculty Research Program Participant

A. M. H. Basher, South Carolina State College, Orangeburg, South Carolina

C. Other Visiting Faculty

C. A. Bennett, Jr., University of North Carolina, Asheville, North Carolina
 K. H. Bhatt, University of Mississippi, University, Mississippi
 S. Kahane, Nuclear Research Center - Negev, Beer-Sheva, Israel

D. Student Intern (Science and Technology Alliance Program)

W. E. Fendleton, North Carolina Agricultural and Technical State University, Greensboro, North Carolina

E. University of Tennessee/ORNL Science Alliance Undergraduate Program Participants

J. Alexander, Evergreen State College, Olympia, Washington
 A. D. Churukian, The College of Wooster, Wooster, Ohio
 R. P. Daniel, Memphis State University, Memphis, Tennessee
 S. D. Graber, Bethel College, North Newton, Kansas
 M. L. Hart, Muskingum College, New Concord, Ohio
 D. W. Lee, Gonzaga University, Spokane, Washington
 C. W. Looney, Gonzaga University, Spokane, Washington
 R. A. Miller, Francis Marion College, Florence, South Carolina
 J. F. Namin, Northeastern State University, Tahlequah, Oklahoma
 M. R. Porter, University of Tennessee, Knoxville, Tennessee

PHYSICS DIVISION SEMINARS: OCTOBER 1989-SEPTEMBER 1990

Seminars arranged by the Physics Division and announced in the ORNL Technical Calendar are listed below. During the period of this report, Edward E. Gross served as Seminar Chairman.

Date	Speaker	Title
1989		
Oct. 5	T.J.M. Zouros, <i>Kansas State University, Manhattan, Kansas</i>	"Observation of Electron-Electron Interactions in Ion-Atom Collisions"
Oct. 26	Jan G. Wouters, <i>Instituut voor Kern-en Stralingsfysica, Belgium</i>	"On-Line Nuclear Orientation: From Technique to New Physics"
Nov. 13	Louise Dolan, <i>Rockefeller Institute, New York, New York</i>	"Getting Physics Out of the String"
Dec. 7	Joseph H. Macek, <i>University of Tennessee, Knoxville, and Division Staff Member</i>	"Theory of Atoms in Strong Fields"
Dec. 19	Richard Hughes, <i>Los Alamos National Laboratory, New Mexico</i>	"New Gravitational Forces and Red-Shift Experiments"
Dec. 20	Kenneth E. Lassila, <i>Iowa State University, Ames, Iowa</i>	"Electromagnetic, Neutrino, and Drell-Yan Probes of Quarks in Nuclei"
1990		
Jan. 16	Ed V. Hungerford III, <i>University of Houston, Houston, Texas</i>	"Strange Things Are Happening"
Jan. 25	Bill Romme, <i>Environmental Sciences Division, ORNL</i>	"Yellowstone National Park Before and After the Fire"
Feb. 8	Norman Tolk, <i>Vanderbilt University, Nashville, Tennessee</i>	"Interaction of Low-Energy Ions, Photons, and Electrons with Surfaces"
Feb. 15	Charles W. Glover, <i>Engineering Physics and Mathematics Division, ORNL</i>	"Neural Networks and Pattern Recognition"
Feb. 21	Carlos Reinhold-Larsson, <i>University of Missouri, Rolla, Missouri</i>	"Classical Monte Carlo Techniques"
Mar. 15	B. Shivakumar, <i>Yale University, New Haven, Connecticut</i>	"Search for Exotic Matter in Nucleus-Nucleus Collisions"
Mar. 19	Stephen Wallace, <i>University of Maryland, Baltimore, Maryland</i>	"Covariant Two-Body Dirac Equation"
Apr. 11	George J. Blamar, <i>Lecroy Research Systems, Spring Valley, New York</i>	"Trends in Data Acquisition Instrumentation"
Apr. 20	Ben Motelson, <i>NORDITA, Copenhagen, Denmark</i>	"Clusters of Metallic Ions -- A Playing Field for Nuclear Physicists"

May 3	Gerald D. Mahan, <i>Solid State Division, ORNL, and the University of Tennessee, Knoxville</i>	"Energy Band Width of Metals"
May 17	Michael K. Miller, <i>Metals and Ceramics Division, ORNL</i>	"Analysis at the Atomic Level: The Atom Probe Field-Ion Microscope"
May 31	Bo Anderson, <i>University of Lund, Sweden</i>	"A Color Rope: Interacting Lund Strings in Heavy-Ion Reactions"
June 21	Keh-Fei Liu, <i>University of Kentucky, Lexington, Kentucky</i>	"Lattice-Gauge Calculations of Hadron Structure and Interaction"
June 22	Michael Plümer, <i>Philipps Universität, Marburg, West Germany</i>	"Space-Time Aspects of Multiparticle Production in Lepton-Nucleus and Nucleus-Nucleus Reactions"
June 28	Jochen Wambach, <i>University of Illinois, Urbana, Illinois</i>	"Dynamics of 'Hot Nuclei'"
July 20	Laurie Waters, <i>Brookhaven National Laboratory, Upton, Long Island, New York</i>	"Energy Flow in 14.6 GeV/Nucleon ^{28}Si Reactions from BNL/AGS Experiment 814"
July 27	Kari S. Vierinen, <i>University of Helsinki, Finland</i>	"Computer Simulations for Gamma Rays and Electrons in Solid-State Detectors"
Aug. 20	Bing An Li, <i>University of Kentucky, Lexington, Kentucky</i>	"Quark Spin Content of the Proton"
Aug. 30	Claude Mahaux, <i>University of Liège, Belgium</i>	"Nuclear Physics in Retrospect"
Sept. 13	Paul Fallon, <i>University of Liverpool, England</i>	"Super-Rigid Nuclei"
Sept. 20	Jack Dongarra, <i>Engineering Physics and Mathematics Division, ORNL, and the University of Tennessee, Knoxville</i>	"Influence of High-Performance Computers on Numerical Software for Dense Linear Algebra"

SCIENTIFIC MEETINGS HELD DURING THIS PERIOD

ORNL Chaos Workshop

Oak Ridge, Tennessee, January 10-11, 1990

J. B. McGrory and K.T.L. Davies, organizers

Hollifield Theory Users Meeting

Oak Ridge, Tennessee, March 23-24, 1990

J. B. McGrory, organizer

Nuclear Structure in the Nineties

Oak Ridge, Tennessee, April 23-27, 1990

N. R. Johnson, organizer

Second UNISOR Nuclear Orientation Workshop

Oak Ridge, Tennessee, July 31 - August 2, 1990

K. S. Krane (Oregon State) and H. K. Carter, organizers

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- 6 - ON LOAN TO OFFICE OF LABORATORY COMPUTING
- 7 - ON ASSIGNMENT TO MANNE BERGMAN INSTITUTE, STOCKHOLM
- 8 - ON ASSIGNMENT TO JAPAN ATOMIC ENERGY INSTITUTE
- 9 - ON LEAVE

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