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PHYSICS DIVISION ANNUAL REVIEW
1 APRIL 1979—31 MARCH 1980

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John P. Schiffer, Division Director

Preceding Annual Reviews:

ANL-77-60, Annual Review 1976—1977
ANL-78-66, Annual Review 1977—1978
ANL-79-40, Annual Review 1978—1979

FOREWORD

The Physics Division Annual Review presents a broad but necessarily incomplete view of the research activity within the Division for the year ending March 1980.

At the back of this report a complete list of publications along with the Divisional roster can be found.

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NUCLEAR PHYSICS RESEARCH

INTRODUCTION

The Physics Division's program in nuclear physics covers a broad span of activities within that discipline. The object of this research is to understand the properties of atomic nuclei, their structure, and the mechanisms of nuclear reactions. Work is carried out under a variety of subprograms: theory, heavy-ion physics, medium-energy physics and nuclear research. These categories do not represent a sharp separation between people—individual scientists often work in several different areas. This flexibility allows scientific problems to be addressed with a variety of techniques, rather than limit individual scientist's activities to a particular subdiscipline.

The Physics Division operates two major accelerators—a much upgraded and modified FN tandem and the superconducting linac booster attached to it, the latter still growing, and the 4-MV Dynamitron. The tandem-linac is used almost entirely for nuclear research by Argonne staff and university users. Less than 25% of the Dynamitron is used for nuclear research. A small program in photonuclear research is carried out at the Chemistry Division's electron linac, and occasionally elsewhere. The medium-energy program is centered at the Los Alamos Meson Physics Facility.

Highlights

In medium-energy physics a new large-acceptance spectrometer was constructed, tested and used at LAMPF in the first survey experiment of inclusive inelastic scattering of charged pions from various nuclei, during the winter of 1980. The analysis of data from the 1979 inclusive (π,p) measurement was carried out and partially completed—an analysis of the proton distributions in the rapidity vs transverse momentum plain suggests that a multinucleon mechanism may be important in pion absorption.

In heavy-ion physics the superconducting linac booster has evolved into a useful accelerator for research. Accelerating fields in excess of 10 MV have been used. The experimental area is beginning to take shape with several beam lines; a large scattering chamber has been commissioned and a beam station for gamma-ray work has been used extensively. Investigation of high spin states near the yrast line has continued, concentrating on the so-called yrast-trap states, and a new sum-spectrometer has been used to study the connection between these states and the continuum. The resonances in the $^{24}Mg(^{16}O,^{12}C)^{28}Si$ reaction have been pinned down by further experimental measurements and detailed analysis.

In charged-particle physics the technique of using the tandem and magnetic spectrograph for detection of very rare radioisotopes has been developed and applied to several problems. The technique has been used to determine the half-life of ^{32}Si (used in dating glaciers) to be a factor of $\sim$3 shorter than the previously accepted value. Also, the cross section for the astrophysically interesting $^{26}Al(p,n)^{26}Mg$(g.s.) reaction was determined.

And in nuclear theory a partly-relativistic few-particle model including the π-N, π-N-N, N-N, and N-Δ channels has been derived as a truncation of quantum field theory and fitted to data for the pion-nucleon, pion-deuteron, and nucleon-nucleon systems. The same model has been used to derive a real optical potential for a distorted-wave impulse approximation treatment of the pion-nucleus interactions. This DWIA theory has been combined with the best available nuclear structure information in a variety of pion-nucleus interactions to show that pions can provide a sensitive probe into the structure of a wide class of nuclear states. The same model is being used in coupled-channel calculations to study the mechanism of the pion double-charge-exchange process.

I. MEDIUM-ENERGY PHYSICS

INTRODUCTION

One of the basic challenges of medium-energy physics is the development of a clear picture of the manner in which pions propagate in nuclear matter. Since the pion is a basic quantum of the nuclear force, understanding its propagation in nuclei contributes to our understanding of the basic nature of nuclear forces. Key to such understanding is a comprehensive and precise experimental description of pion interactions both with complex nuclei and few nucleon systems. This is a major objective of the ANL effort in medium-energy physics. Experiments are carried out as a part of a comprehensive nuclear program, and, because of this perspective, we expect the pion studies to give us new insights into the nature of nuclear forces. At the present time, almost all experimental activity is concentrated on measurements using various pion beams of the Los Alamos Meson Physics Facility.

In one area of study, the Argonne group focuses on measurements of "inclusive" spectra of charged particles and neutral pions from charge-exchange reactions. The most recent measurements are concerned with the study of the competing reaction processes: absorption and inelastic scattering. The results indicate that although the dominant absorption mode mainly involves two nucleons in the very light nuclei, approximately three nucleons interact in ^{12}C and even more in heavier nuclei. For the investigation of the other major reaction mechanism, inelastic pion scattering, a comprehensive series of measurements on nuclei ranging from He to Pb has begun. These studies make use of the ALAS system, which was constructed specifically for this program, but can be used by all LAMPF users as a multipurpose instrument.

High-resolution studies of elastic and inelastic scattering of pions using the EPICS system are another major component of the program. Studies of elastic scattering provide information about the average pion-nucleus interaction and about density distributions. Inelastic scattering to low-lying states of known nuclear structure provides tests and information on the pion nucleus interaction, which can then be used to interpret data for high excitation energies. Inelastic pion scattering seems to be particularly useful for investigating high-spin particle-hole states and elucidating new nuclear structure.

An understanding of pion-nucleus interactions and nuclear structure must ultimately be based upon knowledge of pion-nucleon and nucleon-nucleon interactions. Measurements of deuteron polarization, from both pion and electron scattering, provide a unique method for selecting among various models that describe the fundamental interactions. During 1979, the first successful measurement of tensor polarization in π-d scattering was performed by the Argonne group. The result disagrees with all published theoretical predictions.

A. STUDY OF PION REACTION MECHANISMS

Our knowledge of how pions propagate inside a nucleus is still very incomplete. At the present time both major reaction processes, absorption and inelastic scattering, are still poorly understood. In order to gain additional information an experiment was carried out during 1979 on the Low Energy Pion channel at LAMPF to observe the inclusive charged-particle spectra from π^+ and π^- on a series of nuclear targets. Pion kinetic energies of 60, 100, 160, and 220 MeV were used on targets of ^{4}He, ^{6}Li, ^{9}Be, ^{12}C, ^{27}Al, Ni, and ^{181}Ta. Proton spectra were obtained at angles between 30° and 150° for proton energies between 40 and 250 MeV, from plastic-NaI, ΔE-E telescopes. Integral charged-pion yields were also obtained, without energy measurement. The need to study the complete inelastic pion spectrum and angular distribution was exhibited in the results of the inclusive single-charge exchange $(\pi^\pm,\pi^0)$ survey, where the spectra were dominated by the peak corresponding to charge exchange on quasifree nucleons. The deduced cross sections suggested that a major fraction of the total cross section should result from quasifree inelastic pion scattering. The ALAS system has been constructed so as to study this problem expeditiously. The system also provides a new capability at LAMPF and is expected to be used in a wide variety of experiments.

a. The Two-Nucleon Absorption Mode on ^{4}He

R. D. McKeown, S. J. Sanders, J. P. Schiffer, H. E. Jackson, M. Paul,* J. R. Specht, E. J. Stephenson,† R. P. Redwine,‡ and R. E. Segel§

The proton energy spectra from the inclusive ^{4}He(π^+,p) reaction have been measured as a function of proton angle for incident T_{π^+} = 100, 160, and 220 MeV. At forward angles, these proton spectra exhibit a broad prominent peak at the energy corresponding to "quasideuteron" pion absorption ($\pi + 2N \rightarrow 2N$). The peak is broadened due to the Fermi motion of the nucleons. In addition, the angular distribution of this peak (see Fig. I-1) is essentially the same as that observed in π absorption on the deuteron. The proton yield in this peak is 3 ± 0.3 times the deuteron cross section at all three incident pion energies. When compared to pion absorption cross sections on ^{4}He, this yield accounts for only about 1/3 of the measured absorption cross section of 80 mb.[1]

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[1] H. L. Stadler, Phys. Rev. 96, 496 (1954).

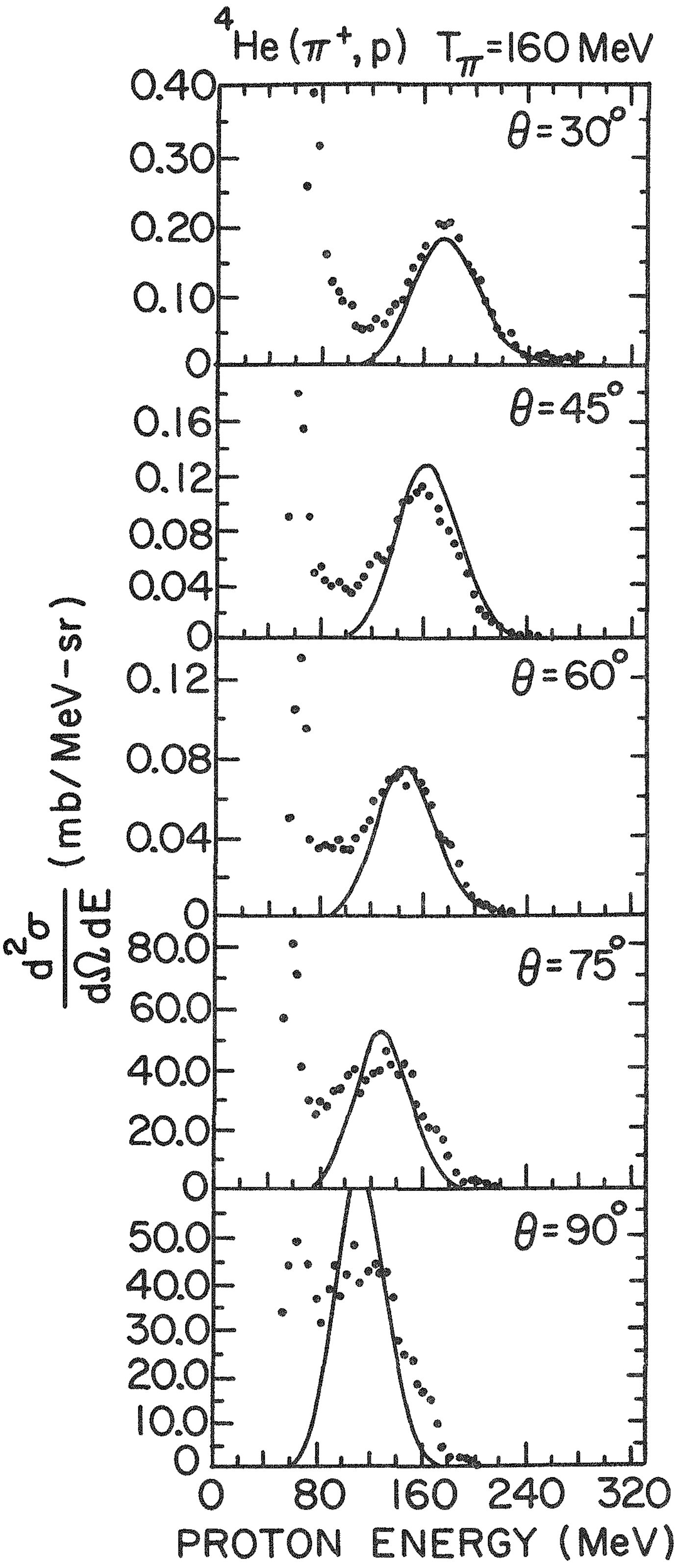

Fig. I-1. The measured proton spectra at the indicated laboratory angles are shown (solid points) along with the calculated 2-nucleon spectra (solid lines) for T_{π^+} = 160 MeV. The calculated curves include effects of binding energy and the Fermi motion of the nucleons in ^4He. The absolute yield is determined by scaling the proton yield from deuterium by a factor of 3.

b. The Number of Nucleons Involved in Pion Absorption

R. D. McKeown, S. J. Sanders, J. P. Schiffer, H. E. Jackson, M. Paul,* J. R. Specht, E. J. Stephenson,† R. P. Redwine,‡ and R. E. Segel§

The proton spectra for targets with $12 \leq A \leq 181$ for $T_\pi = 100$, 160, and 220 MeV have been analyzed. The shift in proton energies with angle may be examined on a contour plot of the invariant cross section in the rapidity vs $p_\perp$ plane (Fig. I-2). From this plot the average number of nucleons that have participated in absorbing the pion's momentum and total energy have been obtained. The effective number of interacting nucleons, for both π^+ and π^- incident, is found to be ∿3 for ^{12}C and increasing to ∿5.5 for ^{181}Ta. These numbers are also consistent with the ratio of protons seen in π^+ and π^- induced reactions.

c. Inclusive Pion Scattering

S. J. Sanders, R. D. McKeown, J. P. Schiffer, H. E. Jackson, M. Paul, J. R. Specht, E. J. Stephenson, R. P. Redwine,‡ and R. E. Segel§

The charged pion yields from 100-, 160-, and 220-MeV π^+ and π^- scattering on targets with $4 \leq A \leq 181$ have been measured over $30° \leq \theta_{lab} \leq 150°$. A plastic scintillator—NaI ΔE-E telescope gave good pion identification without the energy being determined. For $\theta_{lab} > 30°$ the inclusive pion yields are much greater than the elastic cross section and follow the angular distribution of the quasifree π-N process. Using the quasifree π-N process angular distributions to extrapolate the cross sections to forward angles, the pion inelastic yields are found to scale approximately as $A^{0.5}$ (see Fig. I-3).

If one were to assume that the large back-angle pion yield is from the quasifree π-N process, there should be a correspondence between the pion yield and yield of protons at forward angles. A preliminary analysis indicates that for the 220-MeV π^+ scattering the forward proton yield is significantly smaller than expected from the quasifree process.

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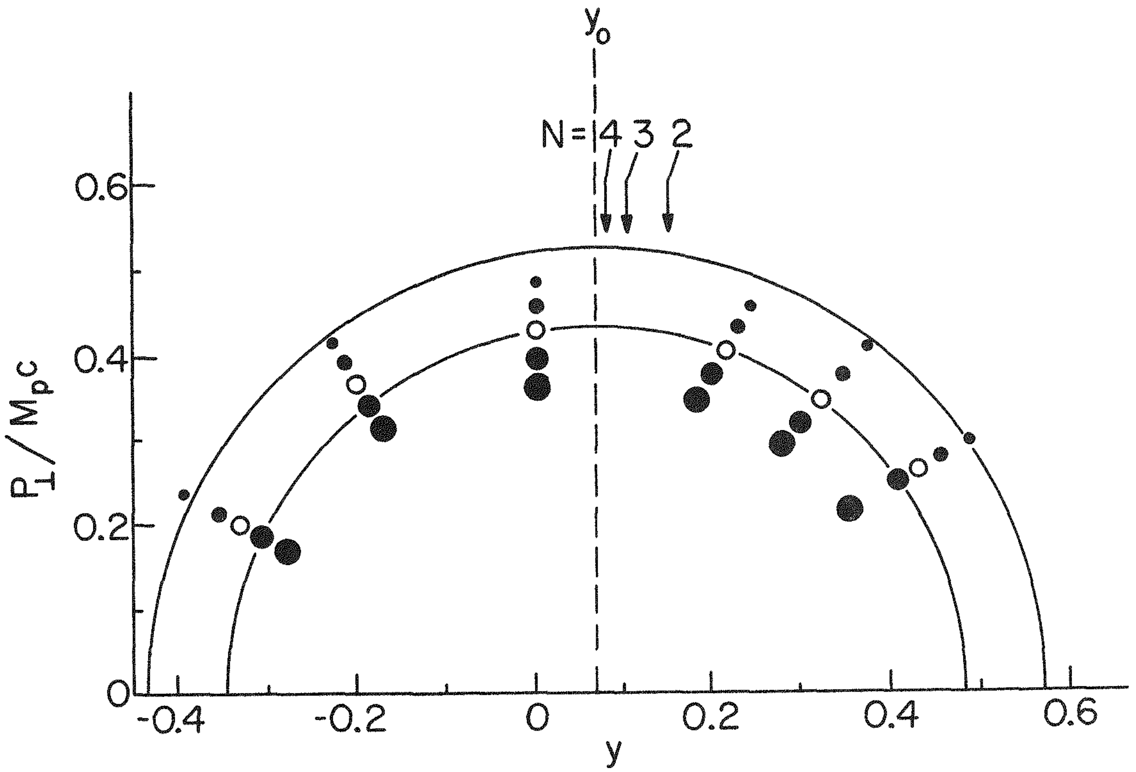

Fig. I-2. Contours of the invariant proton cross section in the plane of rapidity [$y \equiv \tanh^{-1}(\beta_\parallel)$] and ($p_\perp$), for 220-MeV π^- on ^{181}Ta. The points of a given size represent a constant invariant cross section; the largest points are 1.05 $\mu b/(sr\text{-}MeV^2)$; the smaller ones are 0.8, 0.6 (shown as open circles to guide the eye), 0.4 and 0.2 times this value in order of decreasing point size. The rapidity (velocity) of the frame in which the cross section is most nearly isotropic (y_0) is indicated by a dashed line; the contours corresponding to isotropic distributions of protons in this frame with T_p = 82 and 122 MeV are shown as solid lines. The values of rapidity corresponding to the Lorentz frames where the pion is absorbed on 2, 3, and 4 nucleons are indicated by arrows. The laboratory angles of observation corresponding to the different groups of points are also shown.

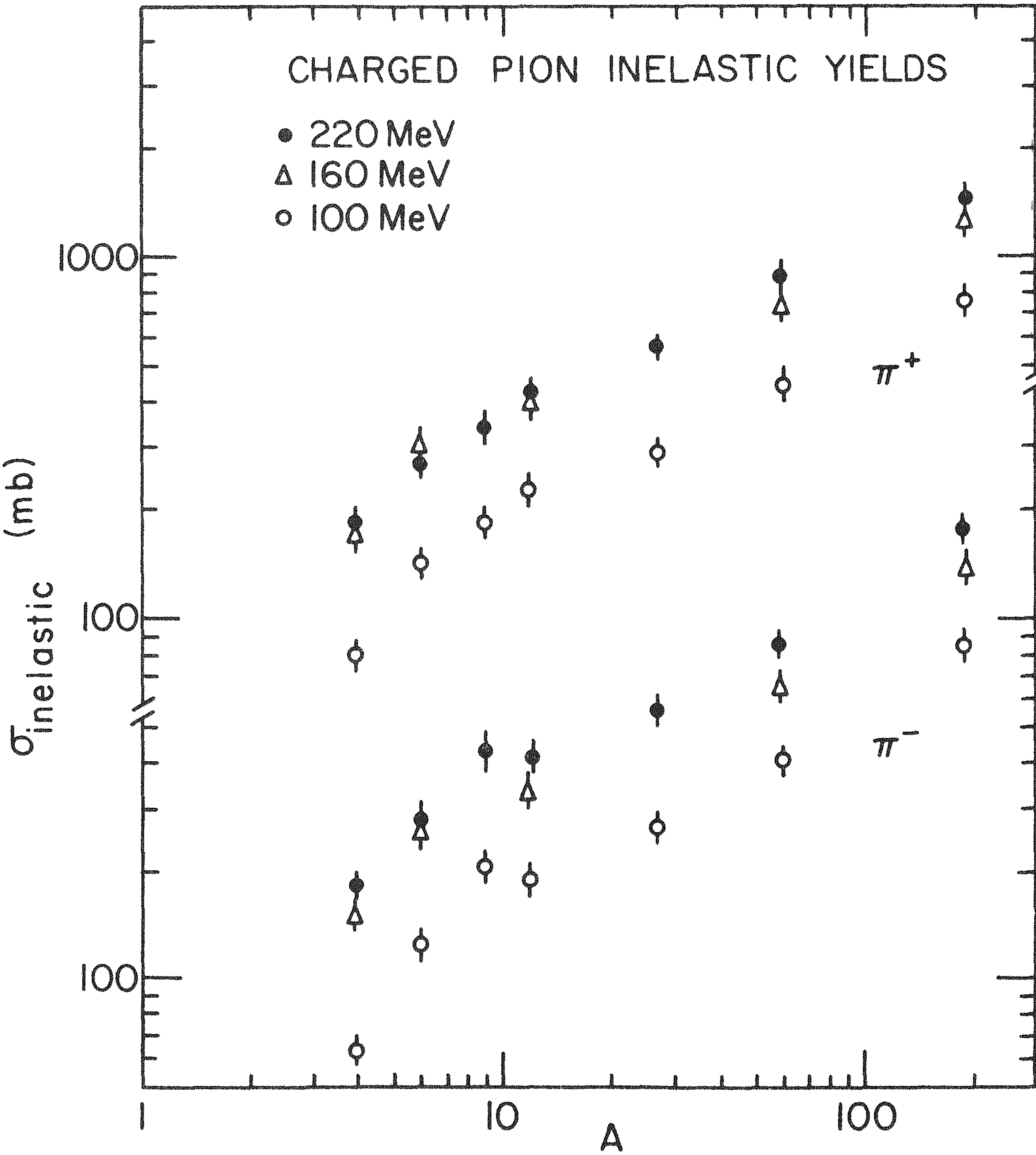

Fig. I-3. The inelastic cross sections obtained by scaling the quasifree π-N angular distribution to the backward angle inclusive pion measurements are plotted as a function of the target mass.

d. Properties of Pion Single-Charge-Exchange Reactions in Nuclei

T. J. Bowles, D. F. Geesaman, R. J. Holt, H. E. Jackson, R. M. Laszewski, J. R. Specht, E. J. Stephenson, R. E. Segel,* R. P. Redwine,† M. A. Yates-Williams,† and J. Julien‡

Pion single-charge-exchange reactions initiated by π^+ and π^- beams have been surveyed on targets ranging from Be to Pb with the use of a back angle γ-ray spectrometer. The beam energy varied from 50 to 150 MeV, and the π^0 spectra were recorded at 6 angles from 25° to 150°. This experiment was an extension of earlier measurements at T_π = 100 MeV and θ = 40° and 120°.[1] The more complete angular distributions determine the total charge-exchange cross section.

The evolution of the charge exchange spectra with angle is illustrated in Fig. I-4 for the $^{16}O(\pi^+,\pi^0)$ reaction. The similarity of the 100-MeV energy-integrated angular distribution to that of the free nucleon suggested by the earlier measurements is confirmed. However, the energy spectra require a substantial multistep contribution be present at forward angles. The observed angular distributions at 50 MeV show large enhancements at forward angles compared to the free-nucleon distributions, also indicating the possible importance of other reaction mechanisms. Integrated charge-exchange cross sections are typically ∿10% of the total reaction cross section.

e. Fermi-Gas Model for π-Nucleus Inclusive Scattering

R. J. Holt and T.-S. H. Lee

Data from systematic studies of pion inclusive scattering from nuclei are becoming available. These data seem to indicate a quasifree peak, particularly at forward angles. As a first step toward understanding the features of these data, we have applied the Fermi-gas model to π-nucleus scattering. The model includes S and P waves in the π-N interaction and off-shell effects. In addition, the effects of N-N correlations were

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[1] T. Bowles, D. F. Geesaman, R. J. Holt. H. E. Jackson, R. M. Laszewski, J. R. Specht, L. L. Rutledge, R. E. Segel, R. P. Redwine, and M. A. Yates-Williams, Phys. Rev. Lett. 40, 97 (1978).

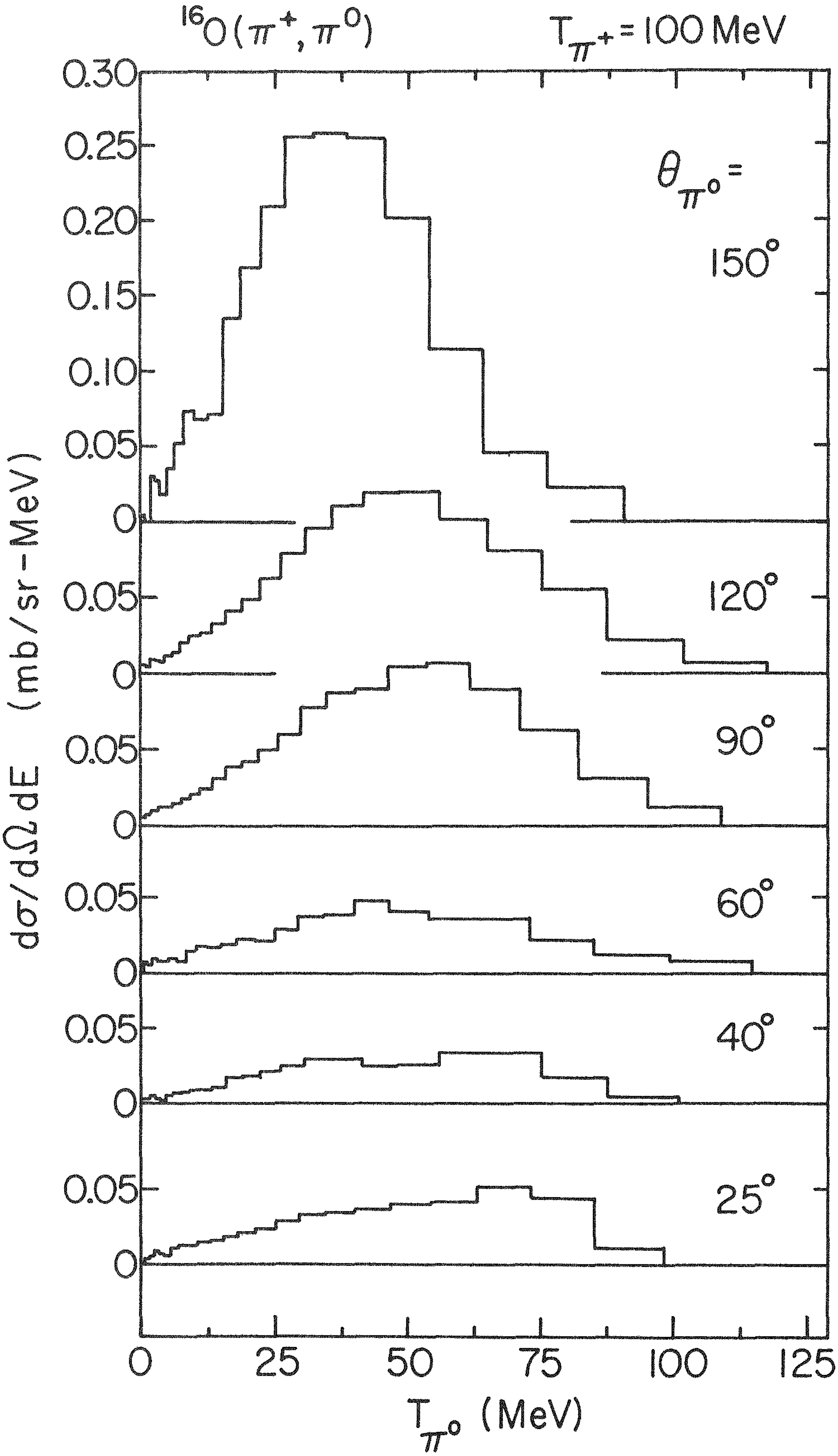

Fig. I-4. π^0 spectra as a function of angle for 100-MeV π^+ incident on ^{16}O.

simulated with a finite temperature Fermi gas. This model is currently being applied to the $^{16}O(\pi^+,\pi^0)$ reaction which was studied by the ANL medium energy group.

f. Argonne Large Acceptance Spectrometer (ALAS)

E. P. Colton,* D. F. Geesaman, R. J. Holt, H. E. Jackson, S. Levenson,† J. P. Schiffer, J. R. Specht, K. E. Stephenson, B. Zeidman, R. E. Segel,‡ P. Gram,§ and C. Goulding||

In collaboration with other groups, Argonne has completed construction of a new utility spectrometer which was placed in operation at LAMPF during cycle 25 in the P^3 channel. The properties of this spectrometer are considerably different than those of existing LAMPF spectrometers and were optimized for large acceptance and moderate energy resolution.

The spectrometer, illustrated in Fig. I-5, consists of a quadrupole doublet followed by a 45° dipole bending magnet; drift spaces are filled with helium gas to reduce multiple scattering.

The detection system consists of three plastic scintillator arrays for differential energy loss and time information, and four multiwire proportional chambers with x and y wire spacings of 0.2 cm.

The wire chambers have individual wire readouts with interfacing accomplished using the PCOS II system. For a momentum acceptance of $\Delta p/p = \pm 15\%$, the solid angle varies over the range 20—25 msr. With the installation of the helium drift system, the resolution of the spectrometer is expected to be $\Delta p/p \approx 0.5\%$ (fwhm) at 500 MeV/c. The ALAS was designed for rapid surveys of pion scattering using existing LAMPF beams. It also offers attractive possibilities for eventual use in coincidence observations of pions with various reaction products, as well as in surveys of rare reaction modes such as double charge exchange. The system has been constructed with the expectation that it will be widely used by all LAMPF experimenters.

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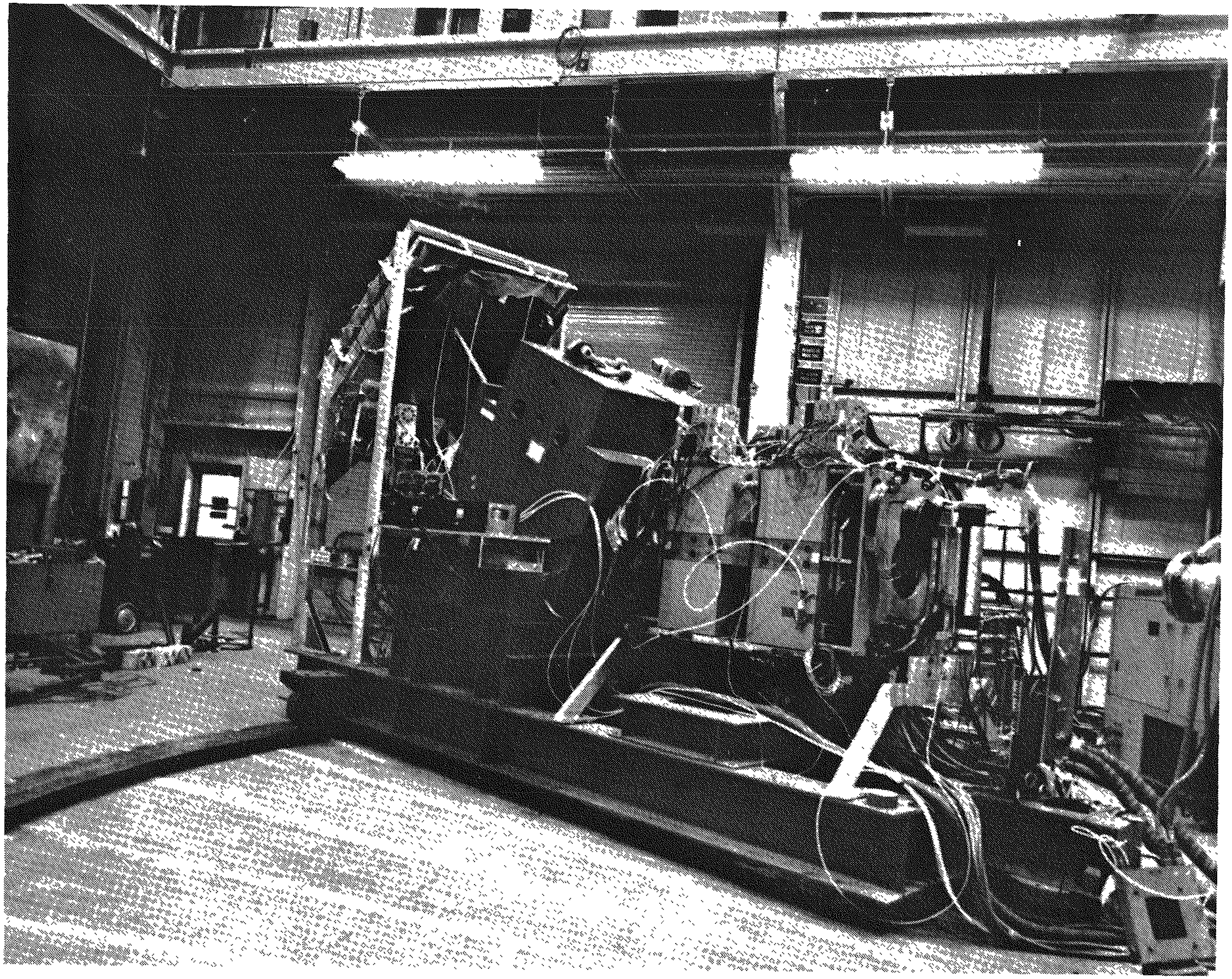

Fig. I-5. The ALAS spectrometer in the P^3-East experimental cave at LAMPF.

g. The Study of Inclusive Inelastic Pion Scattering Near the Δ_{33} Resonance

E. P. Colton,* D. F. Geesaman, R. J. Holt, H. E. Jackson, S. Levenson,† J. P. Schiffer, J. R. Specht, K. E. Stephenson, B. Zeidman, R. E. Segel,‡ P. Gram,§ and C. Goulding||

As a part of a continuing program to determine the major features of pion-nucleus interactions, a comprehensive series of measurements of inelastic pion scattering has been carried out. Inelastic scattering of π^+ from ^{4}He, ^{12}C, ^{58}Ni, and ^{208}Pb was measured at the P^3 channel at LAMPF using the Argonne Large Acceptance Pion Spectrometer, which was constructed specifically for such studies.

Pion momentum spectra were measured at seven scattering angles between 30° and 150° for incident π^+ energies at 100, 160, and 220 MeV. At 160 MeV, π^- data were also taken on ^{12}C and ^{208}Pb targets. Analysis of the data is presently underway. These data, in conjunction with the results of earlier experiments, should provide important information on the distribution of reaction strength in pion reactions, especially on the relation between scattering and absorption channels. The energy spectra of the scattered pions will help determine to what extent quasifree processes are important in determining the character of pion inelastic scattering.

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B. HIGH-RESOLUTION STUDIES AND NUCLEAR STRUCTURE

The high-resolution studies of pion elastic and inelastic scattering using EPICS are primarily focused upon understanding pion-nuclear interactions in terms of their utility for nuclear structure investigations. The program has progressed from measurements of elastic and inelastic scattering which were intended to establish macroscopic behavior in pion-nuclear reactions, e.g., optical-model parameters and collective excitations, to tests of microscopic models of inelastic scattering to low-lying nuclear levels with known wave functions. Concurrently, the data exhibit strong excitation of high-lying levels that are interpreted as arising from stretched particle-hole excitations. Understanding of these data is expected to provide new information on effective interactions that has not been obtainable previously.

a. Scattering of Pions by Complex Nuclei

D. F. Geesaman, C. Olmer, B. Zeidman, G. S. Blanpied,* G. R. Burleson,* M. Devereux,* R. L. Boudrie,† C. L. Morris,‡ H. A. Thiessen,‡ R. E. Segel,§ and L. W. Swenson||

Elastic and inelastic scattering of both π^+ and π^- by ^{9}Be, Si, ^{58}Ni, and ^{208}Pb has been studied at E_π = 291 MeV. The experiment was performed with the EPICS system at LAMPF with an overall system resolution of ∿600 keV. The angular distributions are generally smooth, showing much less structure than those previously measured at E_π = 162 MeV.

The elastic scattering data were described using optical potentials of the Kisslinger form, with parameters fit to the experiment data. Corresponding DWIA calculations for inelastic scattering to states in: ^{9}Be, 2.4 and 6.8 MeV, ^{28}Si, 1.8, 4.6, and 6.9 MeV, ^{58}Ni, 1.5 and 4.5 MeV, and ^{208}Pb, 2.6 MeV, are in reasonable agreement with the data. This is illustrated in Fig. I-6 for the angular distribution of the ^{9}Be states. The deformation parameters required for the even-even targets agree with those obtained from a similar analysis of the 162-MeV data.[1] However, a different deformation

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[1] C. Olmer, D. F. Geesaman, B. Zeidman, S. Chakravarti, T.-S. H. Lee, R. L. Boudrie, R. H. Siemssen, J. F. Amann, C. L. Morris, H. A. Thiessen, G. R. Burleson, M. J. Devereux, R. E. Segel, and L. W. Swenson, Phys. Rev. C 21, 254 (1980).

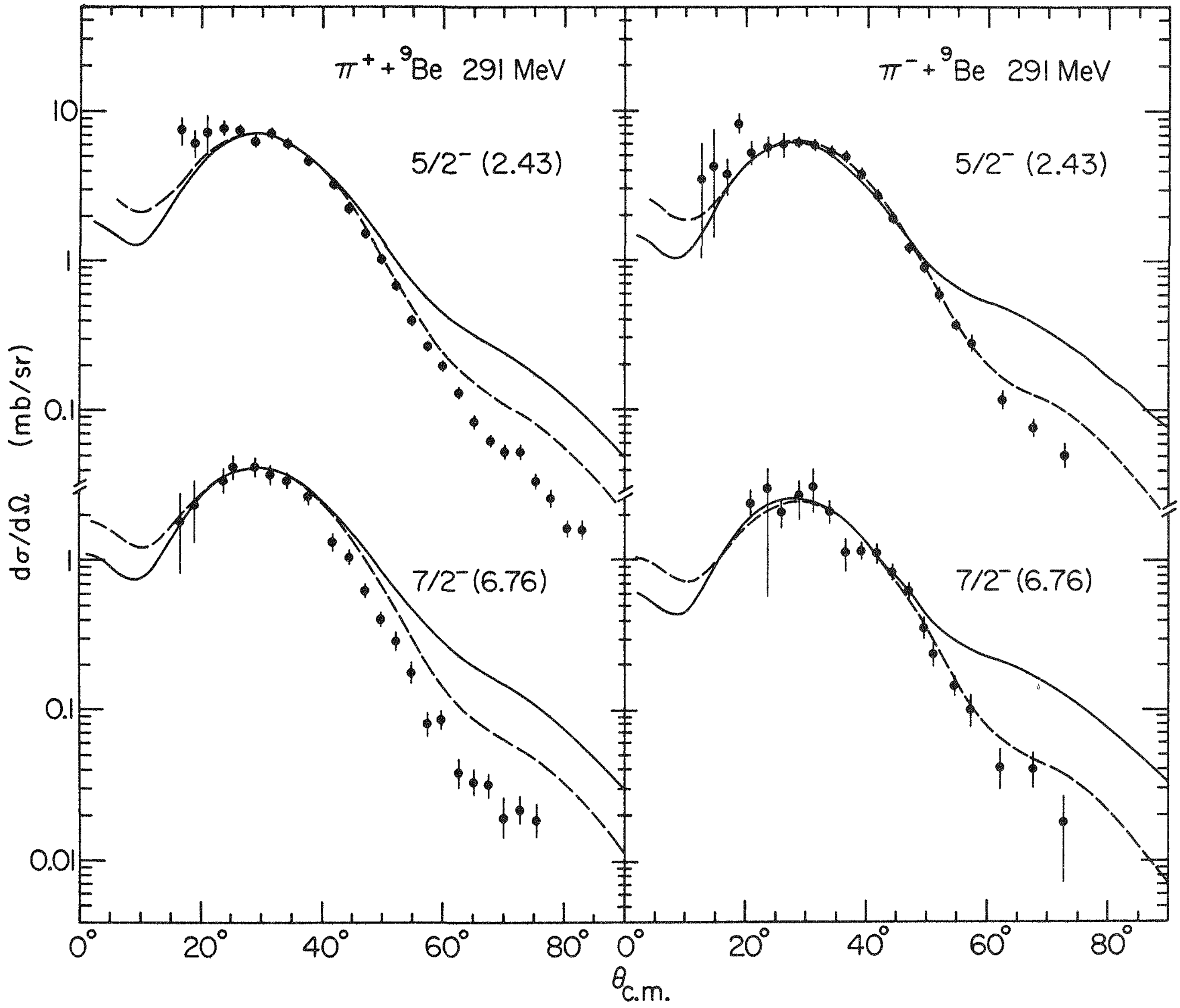

Fig. I-6. Angular distributions for 291-MeV π^+ and π^- inelastic scattering to the 2.43-MeV ($5/2^-$) and 6.76-MeV ($7/2^-$) states in ^{9}Be. The curves are the result of macroscopic DWIA calculations with optical potentials fit to the measured ^{9}Be elastic scattering (solid) and corrected for the large quadrupole contribution to the elastic scattering (dashed).

parameter is required for π^- excitation of the ^{9}Be $7/2^-$, 6.8-MeV state. This is interpreted as evidence for the increased importance of single-particle versus collective components of the nuclear wave functions as the pion energy changes from the 3,3 resonance energy to ∿100 MeV above the resonance energy. Additional efforts utilizing other representations of the optical model are in progress.

b. Determination of Neutron Radii from Pion Scattering

D. F. Geesaman and B. Zeidman

The strong isospin dependence in pion-nucleon interactions near resonance implies a selective sensitivity in pion-nucleus scattering. Analyses of recent high-quality data from ANL and other groups indicate that, on resonance, root-mean-square neutron radii may be deduced. With a modified optical model, preliminary results for neutron-proton rms radius differences obtained from pion scattering are slightly smaller than the n-p differences deduced from high-energy proton scattering, but are consistent within the errors.

c. Excitation of High-Spin Particle-Hole States in ^{28}Si

D. F. Geesaman, C. Olmer, B. Zeidman, T.-S. H. Lee, R. E. Segel,* L. W. Swenson,† R. L. Boudrie,‡ G. S. Blanpied,§ H. A. Thiessen,‡ C. L. Morris,‡ and R. E. Anderson‡

Inelastic scattering of 162-MeV $\pi^{+/-}$ by ^{28}Si has been investigated with the EPICS facility at LAMPF. An overall resolution of ∿270 keV was achieved. π^+ data were taken in 10° steps from 40° to 110° while π^- spectra were only accumulated at 55° and 80°. Among the states seen are the 6^- T=0 and T=1 states at excitation energies of 11.58 and 14.36 MeV, respectively. Angular distributions for these two states, as well as the 9.70 5^- state, are presented in Fig. I-7. The ratio of the cross sections $\sigma(T = 0)/\sigma(T = 1)$ was measured to be $1.5 \pm^{0.4}_{0.2}$ for π^+ and 1.7 ± 0.4 for π^-, as compared to the value 4 expected from DWIA estimates based upon 3,3 resonance dominance.

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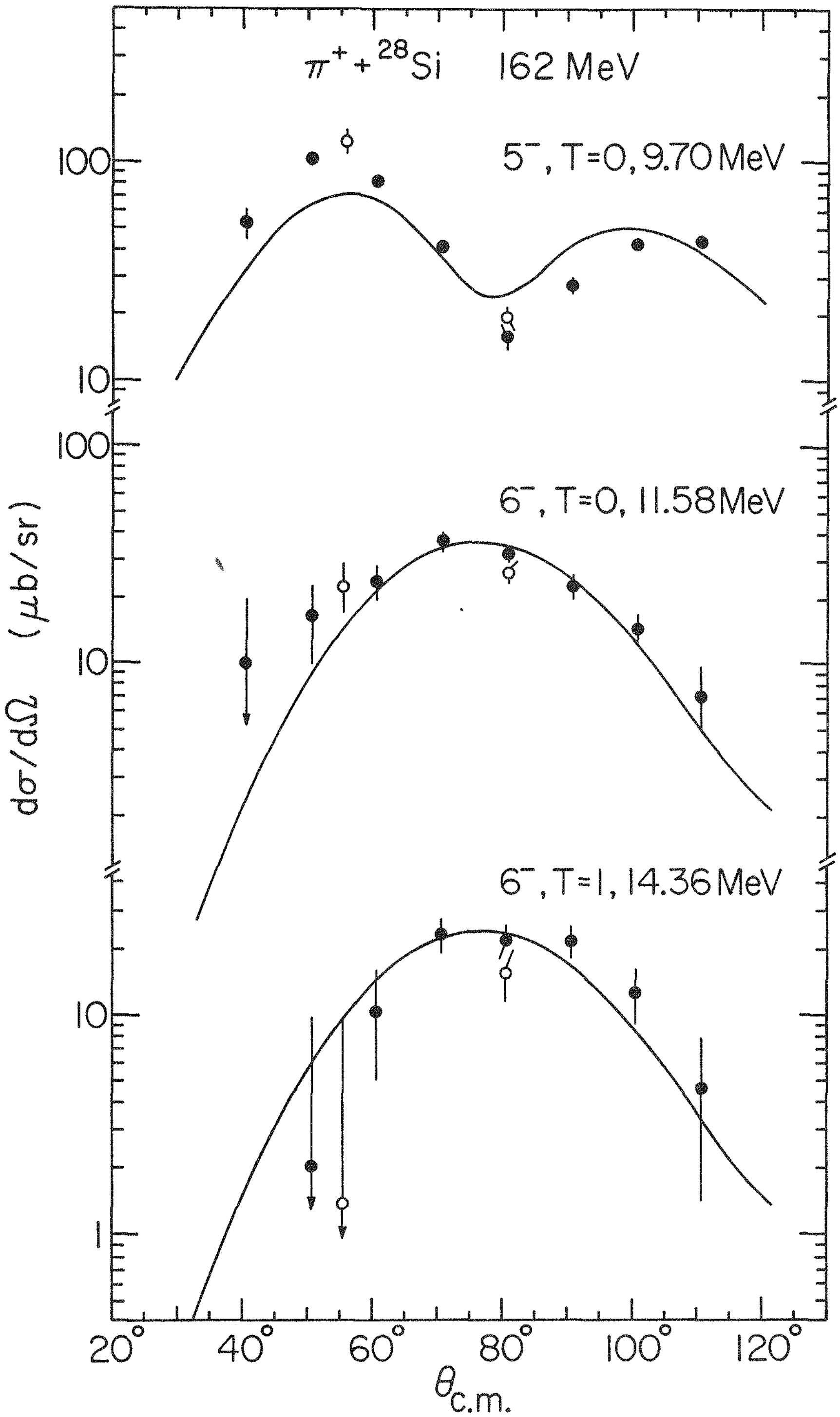

Fig. I-7. Angular distributions for π^+ (solid dots) and π^- (open circles) scattering to the 9.70-MeV (5^-, T=0), 11.58-MeV (6^-, T=0), and 14.36-MeV (6^-, T=1) states in ^{28}Si. The solid lines are the result of microscopic DWIA calculations, with the overall normalization adjusted to the experimental data.

It is not yet clear whether this disagreement is due to the structure at the 6^- states, or to a lack of understanding of the reaction mechanism. However, preliminary data taken at E_{π^+} = 110 and 226 MeV indicate that the experimental ratio may be energy dependent. This suggests that a more correct treatment of the radial structure of the transition density is required in the calculations. A proposal to continue these studies at another incident energy has been approved.

d. Inelastic Pion Scattering from ^{10}B, ^{11}B, and ^{14}N

D. F. Geesaman, C. Olmer, B. Zeidman, G. C. Morrison,* G. Blanpied,† G. R. Burleson,† R. L. Boudrie,‡ R. E. Segel,§ R. E. Anderson,‡ and L. W. Swenson||

Elastic and inelastic scattering of 162-MeV pions from ^{14}N was studied with the EPICS spectrometer at LAMPF. CH_2N_2 and CH_2 targets were employed at each angle, and the nitrogen spectra were constructed by subtraction. Many ^{14}N levels between 3 and 24 MeV were observed, but only an upper limit could be set on the cross section for the 0^+ T=1 state at 2.31-MeV excitation. Optical-model and DWIA analyses are in progress. The angular distributions for most of the states below 10 MeV require L=3 transitions. For the states above 10 MeV, larger L values or spin-flip transitions seem to be required to fit the experimental angular distributions.

Running time has been approved to continue these measurements with ^{10}B and ^{11}B targets. The experiment is scheduled for the fall of 1980.

e. Three-Nucleon Transfer Reactions on ^{11}B

G. C. Morrison,* D. F. Geesaman, W. Henning, and D. G. Kovar

The three-nucleon transfer reactions induced by 30-MeV ^6Li on a ^{11}B target were studied to identify high-spin, 3-particle-1-hole states in A=14 nuclei. Levels in ^{14}N and ^{14}C were observed by detecting the outgoing tritons and ^3He nuclei, respectively, in a Si surface-barrier detector ΔE-E telescope. The purpose of the measurements was to compare the states

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observed in these reactions with those observed in pion inelastic scattering. These data will also provide an important check on the energy calibration of the pion data. Several prominent peaks were identified between 8 and 18 MeV excitation energy in ^{14}N. Analysis is underway to compare the ^{14}N and ^{14}C excitation spectra and determine the isospin of the ^{14}N excited states.

f. Excitation of High-Spin Particle-Hole States in T ≠ 0 Nuclei

D. F. Geesaman, C. Olmer, B. Zeidman, R. E. Anderson,* R. L. Boudrie,* H. A. Thiessen,* R. A. Lindgren,† G. S. Blanpied,‡ G. E. Burleson,‡ R. E. Segel,§ and L. W. Swenson||

The use of pion inelastic scattering as a means of locating and identifying high-spin particle-hole states in T≠0 nuclei was proposed. Targets of ^{54}Fe, ^{58}Ni, ^{88}Sr or ^{90}Zr, ^{120}Sn, and ^{208}Pb will be investigated at EPICS. ^{89}Y may also be studied. The initial measurements will involve both π^+ and π^- scattering at ∿170 MeV, the resonance energy. Further measurements, at a substantially different energy, will be based upon the initial results.

Since high-spin states resulting from the excitation of stretched particle-hole configurations are selectively populated at large momentum transfer, angular distributions consisting of relatively few, widely spaced data points suffice for positive identification of high-spin states. For T≠0 nuclei, these states can arise from either proton or neutron excitation. Because of (3,3) dominance at resonance, scattering of both π^+ and π^- should distinguish between neutron and proton configurations.

g. Discrete States from Pion Double-Charge-Exchange on Heavy Nuclei

B. Zeidman, D. F. Geesaman, R. J. Holt, E. P. Colton,¶ J. R. Specht, and K. E. Stephenson

A proposal to use the ALAS spectrometer on P^3 in a survey of pion double-charge exchange (DCE) reactions to discrete states on a wide variety

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of targets was submitted. Based upon theoretical arguments, it is hoped that the DCE cross section will increase for A > 60 and make it possible to use this reaction as a spectroscopic tool. Targets of ^{58}Ni, ^{90}Zr, ^{120}Sn, and ^{208}Pb will be investigated to establish limits or measure cross sections for transitions to discrete states in the final nuclei. The proposal was approved and running time is expected late in 1980 or in 1981.

C. POLARIZATION MEASUREMENTS

Interactions between two nucleons, as in the deuteron, are the fundamental building blocks of complex nuclei, while the pion is a prime constituent in the nucleon-nucleon interaction. Pion and electron scattering by deuterons are therefore basic ways of probing these interactions in a "simple" system amenable to calculation. The development of a new polarimeter allowed the first measurement of the tensor polarization of the deuteron in π-d scattering to be performed. The result shows the need for further theoretical effort.

a. Measurement of Tensor Polarization and Cross Section for the Reaction $^2H(\pi^+,\pi^+)^2H$ at 180°

R. J. Holt, J. R. Specht, E. J. Stephenson, K. E. Stephenson, B. Zeidman, R. L. Burman,* J. S. Frank,* M. J. Leitch,* J. D. Moses,* M. A. Yates-Williams,* R. M. Laszewski,† and R. P. Redwine‡

Interest in the two-nucleon system has been burgeoning during the past several years. This has been due largely to the development of sophisticated three-body analyses of the π-d system, the experimental evidence for dibaryon resonances, and the development of medium energy probes so that detailed studies can be performed. In addition, the deuteron, being the simplest nucleus, provides a good "laboratory" for testing ideas of the π-nucleus reaction mechanisms since the π-d system can be solved in an exact manner rather than the optical potential approaches. True pion absorption which comprises a significant fraction of pion-induced reaction cross sections has been particularly difficult to incorporate into the theories. This process is believed to involve predominately two nucleons. Thus, the deuteron provides the simplest system for the study of pion absorption effects. The way in which these absorption processes affect the π-d elastic scattering amplitude is difficult to assess from differential cross-section measurements alone. However, recent theoretical predictions[1] indicate that the absorption effects should show up most strongly in the polarization observables. Theoretical predictions of the tensor polarization (t_{20}) are shown in Fig. I-8.

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[1] A. S. Rinat, E. Hammel, Y. Starkand, and A. W. Thomas, Nucl. Phys. A329, 285 (1979).

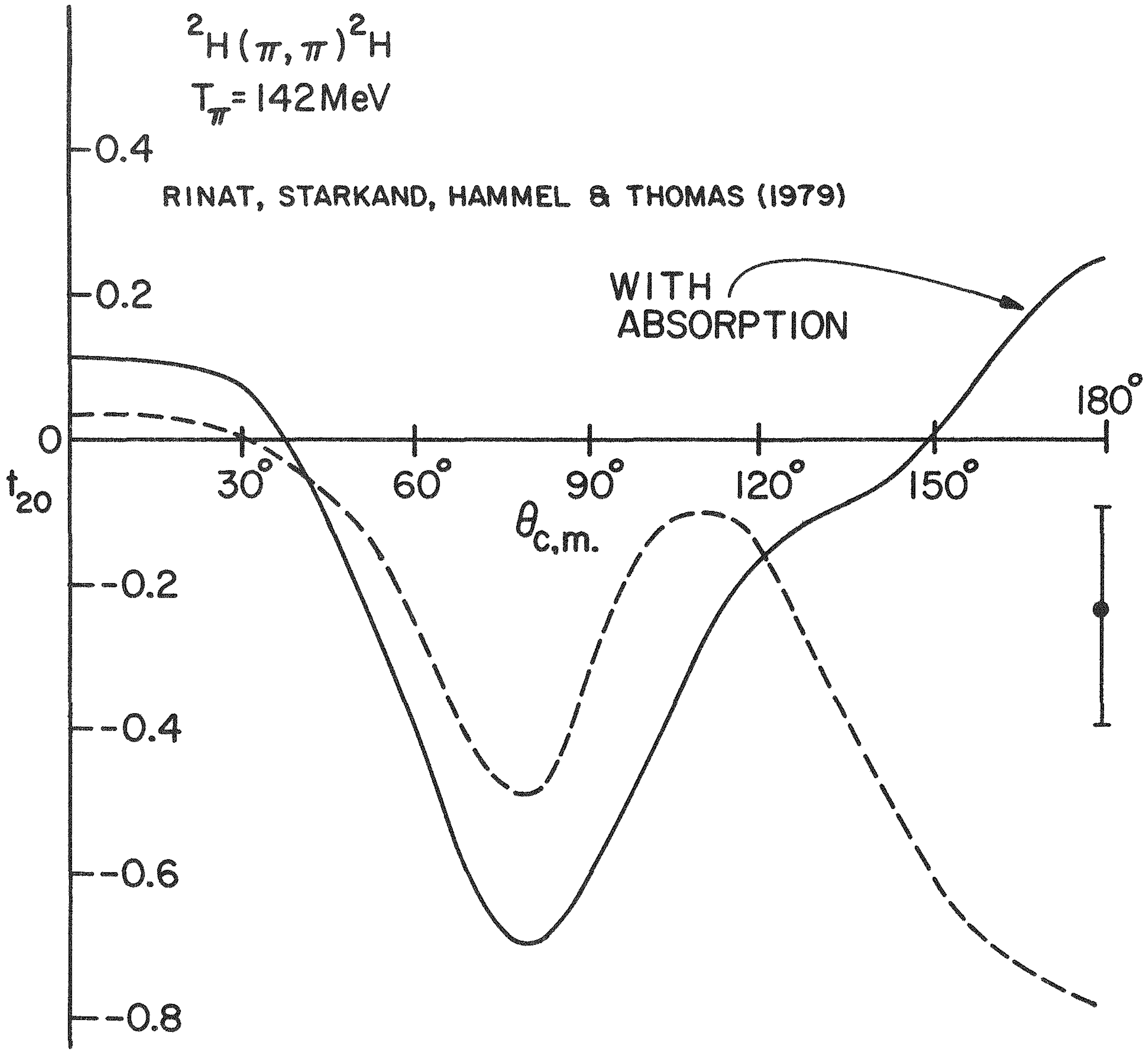

Fig. I-8. Calculations of t_{20} with and without absorption, compared with the present measurement.

The first measurement[2] of t_{20} in π-d elastic scattering was performed using a newly-developed high-efficiency deuteron polarimeter and the LEP channel at LAMPF. The polarimeter which exploits the $^3He(d,p)^4He$ reaction was calibrated using the polarized deuteron beam available at the Berkeley 88-in. cyclotron. At LAMPF the LEP channel was used for both a pion channel and a 0° deuteron spectrometer. The result (see Fig. I-8) of the polarization measurement at T_π = 140 MeV was found to disagree with all theoretical predictions. In addition, the cross section at 180° was measured between T_π = 60 and 140 MeV.

In a separate feasibility study at LAMPF, it was determined that an angular distribution of the tensor polarization could be measured. This is important since the predicted angular dependences are very different at angles larger than 90° as shown in Fig. I-8. Preparations are underway to develop a system to measure the angular dependence of polarization in π-d elastic scattering. It is expected that these measurements will be performed later this year.

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[2]R. J. Holt, J. R. Specht, E. J. Stephenson, B. Zeidman, R. L. Burman, J. S. Frank, M. J. Leitch, J. D. Moses, M. A. Yates, R. M. Laszewski, and R. P. Redwine, Phys. Rev. Lett. 43, 1229 (1979).

b. Deuteron Polarimeter Development

R. J. Holt, J. R. Specht, E. J. Stephenson, K. E. Stephenson, J. S. Frank,* M. J. Leitch,* and J. D. Moses*

Since the demonstration of feasibility of measuring t_{20} in π-d elastic scattering, a more sophisticated polarimeter is being developed for these studies. The characteristics of the first polarimeter were high-efficiency ($\varepsilon_0 = 1.5 \times 10^{-4}$), relatively large analyzing power ($T_{20} = -0.6$) and a wide aperture (~80 cm^2). The new polarimeter will retain all of these properties and it will accept lower deuteron energies than before and provide information about other polarization moments (it_{11}, t_{21}, t_{20}, and t_{22}). The lower energy cutoff (~26 MeV) will make it possible to extend the previous measurement to a more forward angle, while the other moments should provide additional constraints on the theories.

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c. Polarization in e-d Elastic Scattering

R. J. Holt, J. R. Specht, K. E. Stephenson, B. Zeidman, W. Haeberli,* W. Bertozzi,† D. Ingham,† R. P. Redwine,† M. Schulze,† W. Turchinetz,† R. Galoskie,‡ D. W. Saylor,‡ E. J. Stephenson,§ R. L. Burman,|| J. S. Frank,|| M. J. Leitch,|| J. D. Moses,|| and R. M. Laszewski¶

It has long been known that e-d elastic cross sections do not provide a clear distinction between competing N-N potentials. However, theoretical predictions,[1] thus far, have indicated that a measurement of the tensor polarization t_{20} is sensitive to the potential model. In particular, t_{20} is sensitive to the s-wave momentum distribution of the potential while t_{21} is closely related to the tensor force strength. Moreover, a measurement of t_{20} in this reaction would allow one, for the first time, to separate the monopole, quadrupole, and magnetic form factors. These measurements were proposed for the Bates linear accelerator. This work is divided into two phases: (1) low q^2 with $q^2 \leq 9\ fm^{-2}$ which can be performed next year after the π-d experiment and (2) high q^2, with $6 < q^2 < 14\ fm^{-2}$, which would be performed following completion of the beam recirculator at Bates.

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§Indiana University, Bloomington, Indiana.

||Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

¶University of Illinois, Urbana, Illinois.

[1] M. J. Moravcsik and P. Ghosh, Phys. Rev. Lett. 32, 321 (1974); F. Coester and A. Ostebee, Phys. Rev. C 11, 1836 (1975); M. I. Haftel, L. Mathelitsch, and H. F. K. Zingl, preprint.

II. HEAVY-ION RESEARCH AT THE TANDEM AND SUPERCONDUCTING LINAC ACCELERATORS

INTRODUCTION

The heavy-ion research program at the Argonne Physics Division is principally aimed at the study of nuclear structure and its manifestation in heavy-ion induced nuclear reactions. In order to extract information on nuclear structure, measurements with high precision often need to be performed. With the successful operation of the superconducting linac booster, such measurements are now carried out at the tandem-linac accelerator over a wide energy range, extending to energies previously not accessible with high precision beams.

The investigation of high-spin states near the yrast line has provided much new information on the behavior of nuclei at high angular momentum. Argonne work has concentrated on nuclei where high-spin isomers, the so-called yrast traps, are prevalent. In a number of experiments, nuclei with a number of yrast traps have been used as a high-spin laboratory. The studies have focused on extracting the properties of yrast states and on investigating the connection between these and the continuum states. New techniques, including a sum-energy spectrometer, were employed in these studies.

The study of heavy-ion fusion reactions has continued. Additional measurements were performed to understand the resonance-like structures in some fusion reactions. Further measurements of the maximum fusion cross sections confirm its dependence on the nuclear structure characteristics of the reaction partners involved. Such influence of entrance channel effects has also been explored in measurements of different systems leading to the same compound nucleus. First studies with the linac at higher energies indicate the observation of the fusion cross section limit predicted by the liquid drop model.

The resonance effects observed previously in the $^{24}Mg(^{16}O,^{12}C)^{28}Si$ reactions have been further explored through both additional measurements and a new quantitative method of analysis. The measurements were extended in energy and angular range and to various exit channels as well as similar systems. Strong correlations are seen between transitions to some final states. A method of resonance analysis in terms of a Breit-Wigner term added to a direct reaction background has been developed and successfully applied to one of the channels, indicating possibly a more general class of analyses that may lead to an understanding of heavy-ion resonances.

Several measurements were performed to investigate the reaction mechanisms in heavy-ion induced reactions and to map out the distribution of reaction strength as a function of energy and target-projectile masses. With the higher energies from the linac booster, we were able to extend substantially these measurements into energy regions previously not accessible.

We have studied the behavior of the quasi- and deep-inelastic reaction cross sections as a function of energy for medium-heavy systems, the production of inclusive alpha-particle yields for ^{16}O beams at energies $E/A \gtrsim 5$ MeV/nucleon, and excitation functions, mass and kinetic energy distributions for heavy-ion induced fusion-fission reactions.

A major effort during the past year was directed at the development of the new target area for the superconducting linac booster. One beam line with two experimental stations, a general-purpose scattering chamber and a gamma-ray spectroscopy setup with energy sum and multiplicity detectors was completed and successfully used in two linac runs. A second beam line with a large scattering chamber is being completed.

A. RESONANT STRUCTURES IN HEAVY-ION REACTIONS

The observation of resonance-like structures in quasielastic reactions on sd-shell target nuclei has generated considerable interest in the underlying nature of such behavior. At Argonne we have performed extensive studies to explore and understand the strong structures observed in alpha-transfer reactions in the sd shell. Excitation functions at extreme forward and backward angles and a number of angular distributions were measured for alpha transfer on ^{24}Mg. The distribution of decay strength from the high-spin resonances in the ^{40}Ca compound system was investigated by measuring a number of reaction channels to various final states. A schematic resonance analysis, in terms of interfering direct and resonance amplitudes was developed and applied to the ^{24}Mg(^{16}O,^{12}C)^{28}Si data. The calculations suggest that the data are indeed consistent with an interpretation in terms of a few relatively strong resonances. Additional measurements using the higher-energy beams now available from the linac booster were performed to search for resonant structures in even heavier scattering systems.

a. Resonance Analysis of the ^{24}Mg(^{16}O,^{12}C)^{28}Si Reaction

S. J. Sanders, M. Paul, J. Cseh, D. F. Geesaman, W. Henning, D. G. Kovar, R. Kozub, C. Olmer, and J. P. Schiffer

We have continued our investigations of the strong resonance structures observed in the ^{24}Mg(^{16}O,^{12}C)^{28}Si reaction.[1,2] Sufficient data have now been accumulated, including 0°, 90°, and 180° excitation functions, to attempt a coherent analysis in terms of resonant amplitudes adding to a direct reaction background smoothly varying with energy. We have performed such an analysis with resonant amplitudes parameterized by Breit-Wigner energy dependences. This analysis has shown that the full range of data (both in angle and energy) can be understood in terms of a limited number of contributing resonances (see Fig. II-1). We assign spin assignments to strong structures in the 0° excitation functions at 27.6 MeV (ℓ = 20 $\hbar$) and 30.8 MeV (ℓ = 23 $\hbar$). The partial width parameters obtained from this study, which account for only a small fraction of Γ_{tot}, indicate strongly the need to search for correlated structures in other channels sharing the ^{40}Ca compound system.

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[1] M. Paul, S. J. Sanders, D. F. Geesaman, W. Henning, D. G. Kovar, C. Olmer, J. P. Schiffer, J. Barrette, and M. J. LeVine, Phys. Rev. C 21, 1802 (1980).

[2] S. J. Sanders, M. Paul, J. Cseh, D. F. Geesaman, W. Henning, D. G. Kovar, R. Kozub, C. Olmer, and J. P. Schiffer, Phys. Rev. C 21, 1810 (1980).

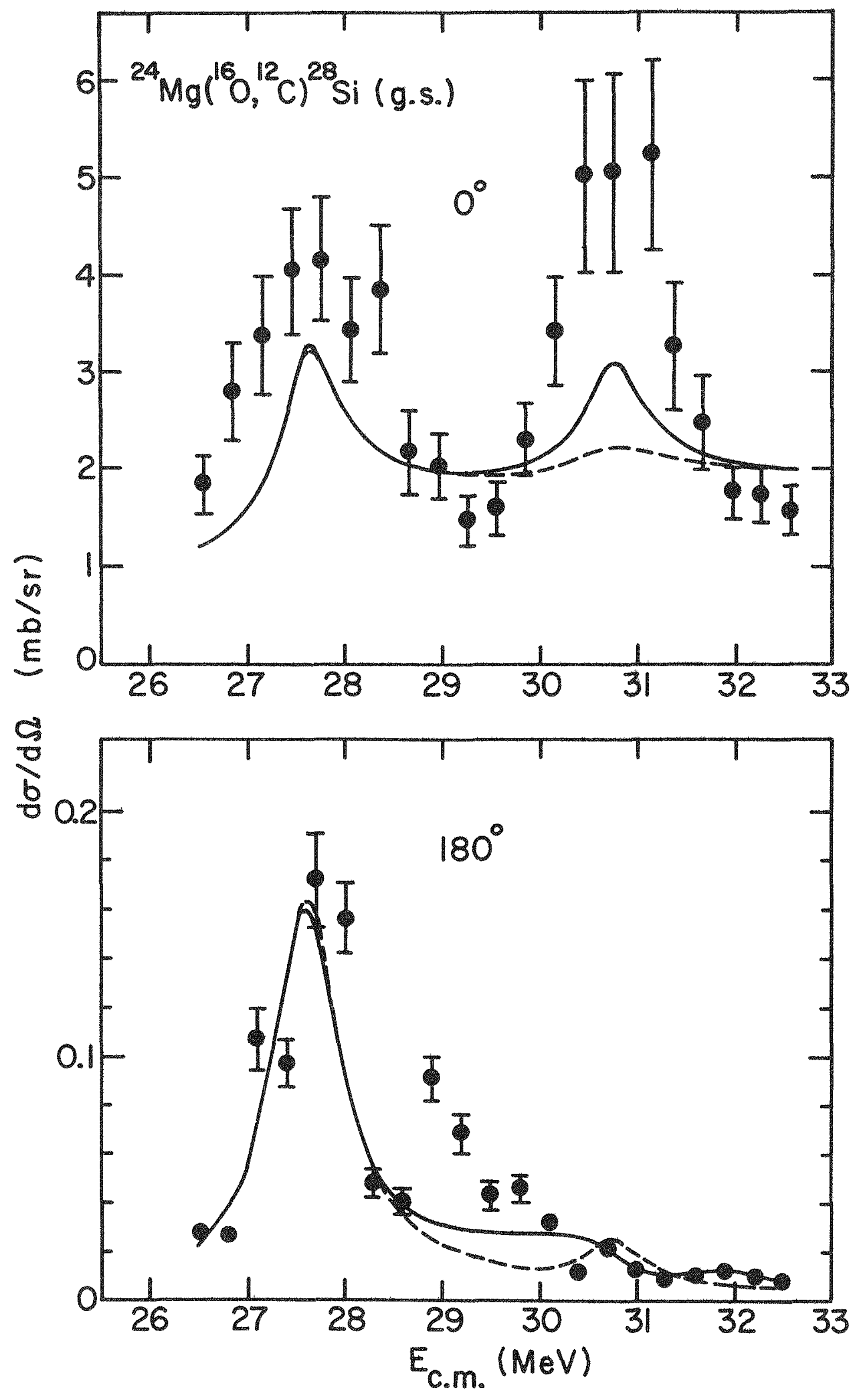

Fig. II-1. Excitation functions for the $^{24}Mg(^{16}O,^{12}C)^{28}Si$ (g.s.) reaction at 0° and 180°. The solid and dashed curves are the results of $\ell = 20 + 23$ and $\ell = 20 + 22$ fits to the data, respectively.

b. Resonance Strength to States at High Excitation Energy in ^{28}Si Populated Via the $^{24}Mg(^{16}O,^{12}C)^{28}Si^*$ Reaction

S. J. Sanders, D. F. Geesaman, W. Henning, D. G. Kovar, C. Olmer, M. Paul, and J. P. Schiffer

To establish the distribution of decay strength from the high spin resonances in the ^{40}Ca compound system, we have measured excitation functions for a number of the open decay channels. Excitation functions for high-energy states in ^{28}Si populated by the $^{24}Mg(^{16}O,^{12}C)^{28}Si$ reaction are found to exhibit resonance behavior which mimics that seen for the ground-state transition. To supplement these excitation functions, which were measured over a limited angular range, more complete angular distributions with $10° \leq \theta_{c.m.} \leq 50°$ were measured at E_{lab} = 50.9 MeV and 54.4 MeV. At these energies, which correspond to a maximum and a minimum in the excitation functions, respectively, the integrated yields for the full angular distributions are found to scale with the excitation functions. An analysis of these data allows an estimate of the partial decay widths to these excited states.

c. Search for Resonance Behavior in the $^{24}Mg(^{16}O,^{20}Ne)^{20}Ne$ Reaction

M. Paul, W. Henning, D. G. Kovar, C. Olmer, S. J. Sanders, and J. P. Schiffer

We have searched for resonance behavior in the $^{20}Ne + ^{20}Ne$, $^{20}Ne + ^{20}Ne$ (2+, 1.63 MeV), and $^{20}Ne(2+) + ^{20}Ne(2+)$ outgoing channels induced by ^{16}O scattering on ^{24}Mg. The mutual 2+ channel is particularly well matched kinematically. Excitation functions were measured at θ_{lab} = 12° and 20° for 25 MeV $\leq E_{c.m.} \leq$ 38 MeV. From a preliminary analysis, there appears to be only slight evidence for structures correlated with those observed in the $^{24}Mg(^{16}O,^{12}C)^{28}Si$ reaction. This analysis is complicated, however, by the energy dependence of the highly oscillatory angular distributions. There is a clear need to measure more extensive angular distribution at a number of different energies.

d. Elastic Scattering of $^{32}S + ^{24}Mg$

R. Betts,* B. Back,* W. Henning, and K. Wolf*

Recent work on $^{28}Si + ^{28}Si$ elastic scattering has shown resonance-like behavior in the 90° excitation function. The present experiment was

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performed to provide data for the $^{32}S + ^{24}Mg$ system, which leads to the same compound nucleus, and to see if any correlations exist between the two. Excitation functions for elastic and inelastic scattering to the low-lying states were measured over an energy range $85 \leq E_{lab}$ (^{32}S) ≤ 150 MeV. Preliminary analysis indicates that the $^{32}S + ^{24}Mg$ cross section for elastic scattering is considerably smaller than that for $^{28}Si + ^{28}Si$ and no evidence is seen for structure of width similar to that in $^{28}Si + ^{28}Si$. The origin of this difference is presently being investigated in terms of coupling of entrance channel resonances to compound nuclear, inelastic and transfer degrees of freedom.

B. FUSION CROSS SECTIONS

Over the past four years a program of measurements has been carried out in the Argonne Physics Division to explore the systematic trends in the fusion cross sections of heavy ions. Particular emphasis has been on the manifestation of nuclear structure effects, as observed in resonance-like structures and the maximum cross-section values in various systems. These measurements have now been extended to the heavier systems and in particular to higher incident energies, provided by the beams from the linac. There is considerable interest in such measurements over a large range of energies in order to establish unambiguously the saturation values of the maximum fusion cross sections and the cross-section limits predicted by liquid-drop calculations. The first results at the linac are indeed indicative of the predicted liquid-drop limits.

a. Fusion Cross-Section Behavior for $^{12}C + ^{24,26}Mg$

K. Daneshvar,* D. G. Kovar, and C. N. Davids

Both charged-particle and gamma-ray measurements were performed to investigate the fusion cross-section behavior for the $^{12}C + ^{24,26}Mg$ systems. The studies were motivated by the observations that the total fusion cross-section excitation functions for some "α-cluster" light heavy-ion systems (namely, $^{12}C + ^{12}C$, $^{12}C + ^{16}O$, and $^{16}O + ^{16}O$) exhibit resonance-like structures, while similar systems with an excess of a nucleon or two appear smooth.[1] Of interest is whether such structures persist in heavier systems. The charged-particle measurements of the evaporation residuals revealed that the excitation functions of the total fusion cross sections for $^{12}C + ^{24}Mg$ show the presence of structures, while that for the $^{12}C + ^{26}Mg$ system appears relatively smooth.[2] This is shown in Fig. II-2, where the total fusion cross sections for the $^{12}C + ^{24,26}Mg$ systems are plotted versus the center-of-mass energy $E_{c.m.}$. To further substantiate the presence of the structures, and establish the evaporation channels with which the structure is associated, γ-ray measurements for the $^{12}C + ^{24}Mg$ system were performed. In this study, the γ rays associated with the evaporation residues were detected using a Ge(Li) detector and their yields were extracted

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*Thesis student, University of Illinois, Chicago Circle Campus, Chicago, Illinois.

[1] D. G. Kovar *et al.*, Phys. Rev. C 20, 1305 (1979).

[2] K. Daneshvar *et al.*, Bull. Am. Phys. Soc. 24, 666 (1979).

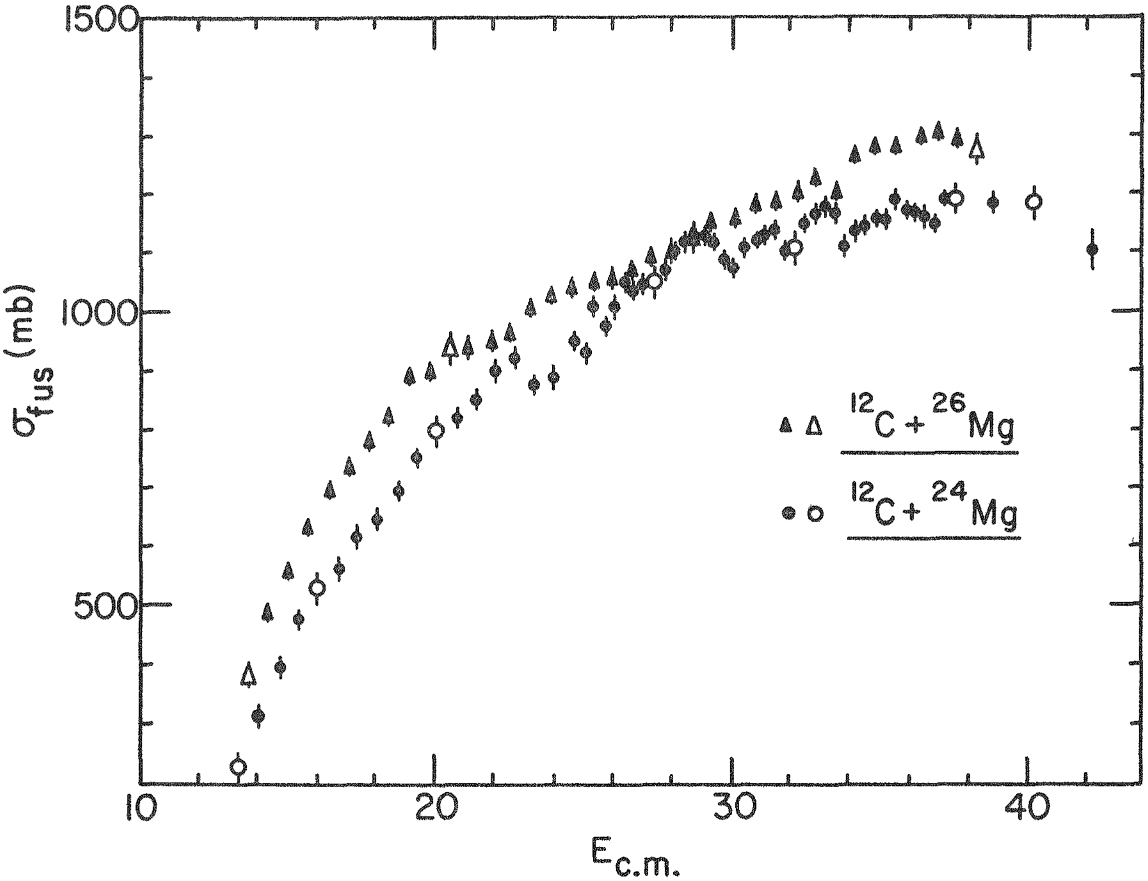

Fig. II-2. The total fusion cross sections σ_{fus} from the $^{12}C + ^{24,26}Mg$ systems are plotted versus $E_{c.m.}$. The open symbols indicate energies at which full angular distributions were measured, and the solid symbols indicate that single angle ($\theta_{lab} = 8°$) measurements were made. Relative errors are shown; absolute uncertainties are ≈5—7%.

as function of bombarding energy. These measurements, performed in $\approx$250-keV steps over the energy range $20 \leq E_{lab}(^{12}C) \leq 50$ MeV, revealed that prominent structure is present in the γ-ray yields associated with ^{28}Si and ^{24}Mg which correspond to the 2α- and 3α-evaporation channels, respectively. The γ-ray yields for the other evaporation channels were found to have a smooth energy dependence. These studies show that resonance-like structures are present in the fusion cross-section excitation function for $^{12}C + ^{24}Mg$, and that with the addition of two neutrons (i.e., $^{12}C + ^{26}Mg$) such structure disappears. Further charged-particle and γ-ray measurements to study the relationship between structure seen in the fusion cross sections and similar structures observed in various direct reaction channels are planned.

b. The Fusion of $^{24}Mg + ^{24}Mg$

C. M. Jachcinski, C. N. Davids, D. F. Geesaman, D. G. Kovar, C. Olmer, M. Paul, S. J. Sanders, and J. L. Yntema

Oscillatory structures have been observed in the excitation functions of total fusion cross sections for $^{12}C + ^{12}C$, $^{16}O + ^{12}C$, and $^{16}O + ^{16}O$,[1] and at a much weaker level, for $^{28}Si + ^{28}Si$.[2] We have studied the fusion of $^{24}Mg + ^{24}Mg$ to search for structure in the excitation function for this system. The evaporation residues resulting from fusion were detected in a ΔE-E gas-ionization-chamber-silicon surface-barrier detector system. Evaporation residue and elastic scattering angular distributions were measured at E_{lab} = 50 and 64 MeV, and single-angle measurements (θ_{lab} = 5.0°) were performed from E_{lab} = 50 to 64 MeV in 1-MeV steps. The general energy dependence of the cross section is in good agreement with the systematics of fusion reactions. The data suggest the possibility of weak oscillatory structures in the excitation function at the 5% level. (See Fig. II-3.) Gamma-ray measurements are in progress in an effort to pin down the strength of the oscillations and their exit channel dependence.

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[1] D. G. Kovar *et al.*, Phys. Rev. C 20, 1305 (1979).

[2] S. B. Dicenzo *et al.*, Bull. Am. Phys. Soc. 23, 949 (1978).

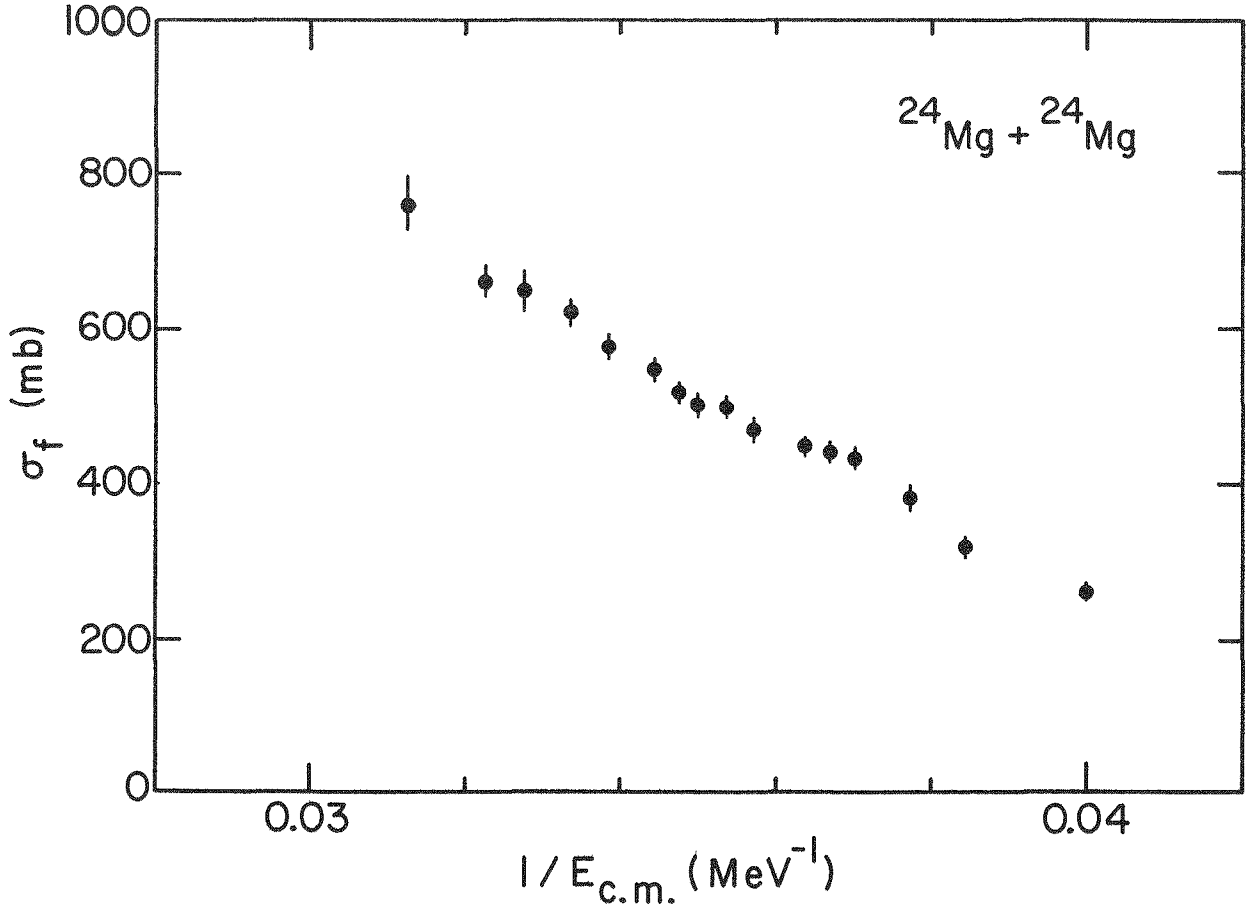

Fig. II-3. Cross section for complete fusion for the $^{24}Mg + ^{24}Mg$ system, as determined by charged-particle measurements.

c. Influence of the Entrance Channel on the Fusion Process

F. W. Prosser, Jr.,* R. Racca,* C. N. Davids, and D. G. Kovar

Charged-particle measurements of the total fusion cross-section behaviors for the systems $^{15}N + ^{27}Al$, $^{16}O + ^{26}Mg$, and $^{18}O + ^{24}Mg$ (which all form the compound nucleus ^{42}Ca) have shown that there are differences in the energy dependences which have been interpreted as evidence for an entrance-channel effect.[1,2] To investigate this we have initiated a series of γ-ray studies in which the γ-ray transitions associated with the evaporation residuals have been measured as function of projectile-target combination and bombarding energy. These measurements are sensitive to small differences in the distribution of fusion strength among the various evaporation channels and to the presence of possible structure in the energy dependence, and hence should provide an excellent way of studying an entrance-channel dependence. Measurements have been performed at five energies over the energy range $30 \leq E_{lab} \leq 60$ MeV for the systems $^{16}O + ^{24,26}Mg$ and $^{18}O + ^{24}Mg$, and the results are being analyzed. Future measurements are planned for the $^{15}N + ^{27}Al$ system, and for the fine step excitation functions for the other systems. The results of the γ-ray studies, together with evaporation model calculations, will hopefully provide information about how the detailed structure of the projectile and target plays a role in the fusion process.

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*University of Kansas, Lawrence, Kansas.

[1] F. W. Prosser, Jr., R. A. Racca, K. Daneshvar, D. F. Geesaman, W. Henning, D. G. Kovar, K. E. Rehm, and S. L. Tabor, Phys. Rev. C 21, 1819 (1980).

[2] S. L. Tabor, D. F. Geesaman, W. Henning, D. G. Kovar, K. E. Rehm, and F. W. Prosser, Jr., Phys. Rev. C 17, 2136 (1978).

d. Fusion of $^{16}O + ^{24,26}Mg$ at Higher Energies

D. G. Kovar, C. Jachcinski, C. N. Davids, D. F. Geesaman, W. Henning, and S. J. Sanders

Previous measurements[1] of the $^{16}O + ^{24,26}Mg$ reactions have established the fusion cross-section behavior over the energy range $30 \leq E_{lab}(^{16}O) \leq 80$ MeV. It was found that the fusion cross sections "saturate" $(\sigma_{fus}^{max} \gtrsim 1100$ mb$)$ at $E_{lab} \gtrsim 60$ MeV with the cross sections for $^{16}O + ^{26}Mg$

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[1] S. L. Tabor *et al.*, Phys. Rev. C 17, 2136 (1978).

approximately 100 mb larger than those for $^{16}O + {}^{24}Mg$. In the present study, the interest was to extend the fusion measurements to the higher energies obtainable with the superconducting linac booster, and to establish whether differences between the two systems continue to exist and whether the behaviors are consistent with the predictions of various models proposed. Angular distributions for elastic scattering and the evaporation residue yields were measured at $E_{lab}(^{16}O)$ equal to 60, 100, and 138 MeV using a gas ionization counter-silicon surface barrier detector ΔE-E telescope. The evaporation residue cross sections for both systems were found to remain approximately constant in magnitude ($\sigma_{fus} \approx 1100$ mb) up to an energy of $E_{lab} \approx 100$ MeV and to decrease at higher energy. The similarity of the magnitudes of the cross sections argues against any strong dependence on the structure of the nuclei involved. The decrease of the cross sections at the highest energies needs further investigation.

e. Coincidence Measurements Between Evaporation Residues and K x Rays in Heavy-Ion Induced Complete Fusion

H. Ernst, C. N. Davids, W. Henning, and S. J. Sanders

The study of x rays emitted in heavy-ion collisions shows some interesting features both with respect to atomic and to nuclear physics. In particular, measurements of singles yields and K x-ray multiplicities with coincidence techniques[1] may provide a useful tool for determining absolute compound nucleus reaction cross sections and transition multipolarities of high-multiplicity γ cascades.

We have started experiments investigating the $^{28}Si + {}^{48}Ti$ reaction at tandem energies and the $^{28}Si + {}^{60}Ni$ reaction using the superconducting linac. Preliminary results obtained in the linac experiment are discussed here. A self-supporting 240 $\mu g/cm^2$ ^{60}Ni target was bombarded with a 173-MeV $^{28}Si^{13+}$ beam. A singles measurement of the evaporation residues over the full angular range with a silicon ΔE-E telescope yields a total fusion cross section of $\sigma_f = 1070$ mb with an uncertainty of $\sim$10%. The evaporation residues were clearly identified; however, no individual Z's were resolved.

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[1] H. J. Karwowski, S. E. Vigdor, W. W. Jacobs, S. Kailas, P. P. Singh, F. Souga, and W. D. Ploughe, Phys. Rev. Lett. 42, 1732 (1979) and references therein.

The evaporation residue K x rays were observed with an SiLi detector, which was placed close to the target at 90° to the beam axis. A 12.7 mm thick lucite absorber reduced the strong yields from the Ni characteristic x rays. The relative yields of the strongest fusion channels are estimated as 0.9:1.0:0.7 for Y, Zr, and Nb, respectively. In order to measure the K-x-ray multiplicity, coincidence spectra were taken between the ΔE-E telescope at 6° and the SiLi detector. A time spectrum was generated by start pulses from the SiLi detector and stop pulses from the E detector, delayed by 180 ns. Gating on the evaporation residues in the ΔE-E spectrum, and on the region in the SiLi spectrum which corresponds to the energies of the fusion product x rays, a definite peak appears in the time spectrum (see Fig. II-4); the position and width of the time peak agrees well with that calculated from the velocity distribution of the evaporation residues. From the coincidence rate and the singles fusion events in the ΔE-E telescope, the K-x-ray multiplicity is derived to be 0.004 ± 0.001. The derived multiplicity is nearly three orders of magnitude lower than that measured in heavier systems,[1] and in fact agrees with the value estimated for the atomic contribution to the K-vacancy production cross section alone.

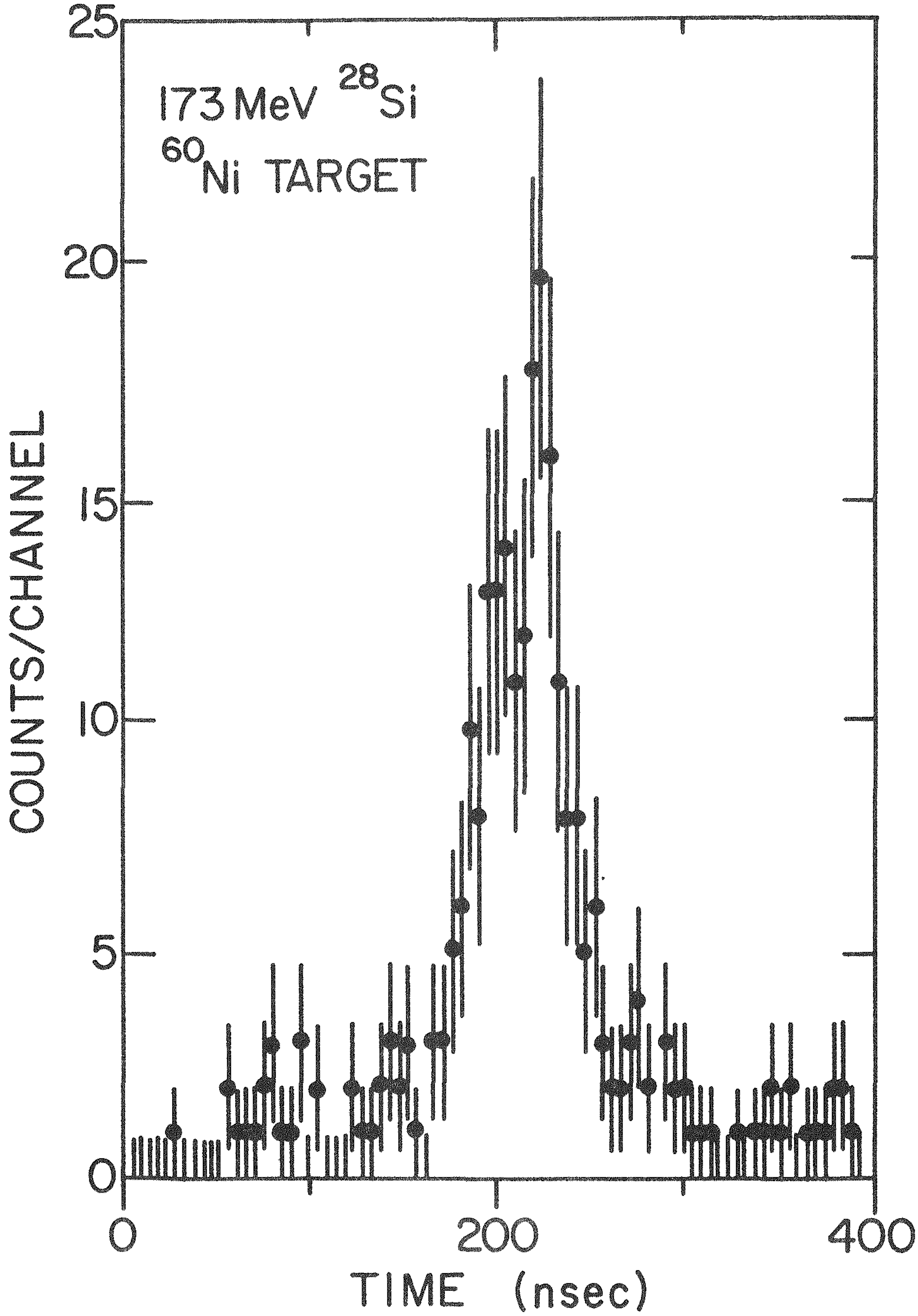

Fig. II-4. Coincidence time spectrum between the fusion evaporation residues and the SiLi x-ray detector.

C. HIGH ANGULAR MOMENTUM STATES IN NUCLEI

Our studies have focused on extracting the properties of yrast states at very high spin and on investigating the connection between these and the continuum states. In a number of experiments we have used ^{151,152}Dy as a "laboratory" of high spin phenomena, since we have determined the yrast states in these nuclei to the highest spin to date ($I \sim 37$).

Work on earlier experiments done at Chalk River is being completed and our present experiments are being conducted using ^{32}S and ^{34}S beams from the Argonne superconducting linac booster. The γ-ray facility is now essentially complete, with target chambers and detector supports in place. In addition, a sum spectrometer consisting of two 13-in. × 6-in. NaI crystals, each segmented into optically separate quadrants, is now operational and has been used in several experiments.

a. High Spin Structure of ^{148}Dy

T. L. Khoo, B. Haas,* H. R. Andrews,* O. Häusser,* P. Taras,* D. Ward,* C. N. Davids, and W. Kutschera

This work constitutes part of our systematic studies on the yrast lines of Dy isotopes as a function of neutron number outside the N=82 closed shell. For ^{148}Dy, which has a closed N=82 shell and 2 protons outside the Z=64 closed shell, core-excited configurations should occur at lower spin than in the heavier Dy isotopes we have studied. The breaking of the closed shells could result in increased deformability of the core and the possibility of oblate deformation. The data analysis is still in progress. The preliminary level scheme shows that the yrast line rises steeply with spin for 4 states above a $(\pi h_{11/2}{}^2)10^+$ isomer, but levels off thereafter up to the maximum observed spin of 20 ħ. It remains to be explored whether this latter feature indicates the onset of deformation.

b. Spectroscopy of High-Spin States in ^{150}Dy

W. Kutschera, I. Ahmad,† J. Borggreen, C. N. Davids, T. L. Khoo, S. Levenson,‡ and R. K. Smither

The level structure of ^{150}Dy has been studied as part of a systematic investigation of very high spin states found in the neighboring

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isotopes ^{151,152}Dy. 140- to 160-MeV ^{32}S and ^{34}S beams from the superconducting linac have been used to populate high spin states in ^{150}Dy via the ^{122}Sn(^{32}S,4n) and ^{120}Sn(^{34}S,4n) reactions. Extensive γ-ray spectroscopy including excitation function, prompt and delayed γ rays, γ-γ coincidences and angular distribution measurements have been performed. The resulting level scheme indicates that ^{150}Dy resembles the simple cascade structure of ^{151,152}Dy up to about spin 21. Above this value, the level scheme becomes more complex in ^{150}Dy resulting in different γ branches and in a maximum spin value which is low by about 6—8 units as compared to ^{151,152}Dy. In addition, no isomers exceeding a 3 ns half-life have been found in contrast to long-lived states of 10—60 ns found in ^{151,152}Dy. These results indicate that there might be a considerable structural change taking place in the highest spin region toward the more neutron deficient Dy isotopes.

c. Very High Spin Yrast States in ^{151}Dy

T. L. Khoo, R. K. Smither, I. Ahmad,* C. N. Davids, W. Kutschera, S. Levenson,† B. Haas,‡ H. R. Andrews,‡ O. Häusser,‡ D. Horn,‡ J. F. Sharpey-Schafer,‡ P. Taras,‡ W. Trautmann,‡ and D. Ward‡

We have employed an extensive set of γ-ray experiments in conjunction with the (^{32}S,5n) reaction to complete our investigation of the yrast levels of ^{151}Dy with spins of up to 71/2 (Fig. II-5). The beams have been provided by the Chalk River MP Tandem and the Argonne superconducting linac. For $I > 29/2$ the yrast energy increases linearly with $I(I + 1)$, on the average, with an effective moment of inertia 13% larger than the rigid sphere value. Comparison of the observed yrast line with that estimated from a shell model approach suggests an average oblate deformation for $I \geq 29/2$ of $\beta \sim 0.18 \pm 0.08$ along the yrast line. This deformation may be partially attributed to the repeated occurrence over a large spin interval along the yrast line of configurations with maximal or near maximal alignment and the subsequent core polarization. The occurrence of core-excited yrast states ($Z = 64$ and $N = 82$ are assumed to form the core) for $I > 53/2$ also plays an important role in achieving the oblate deformation. Unusually large

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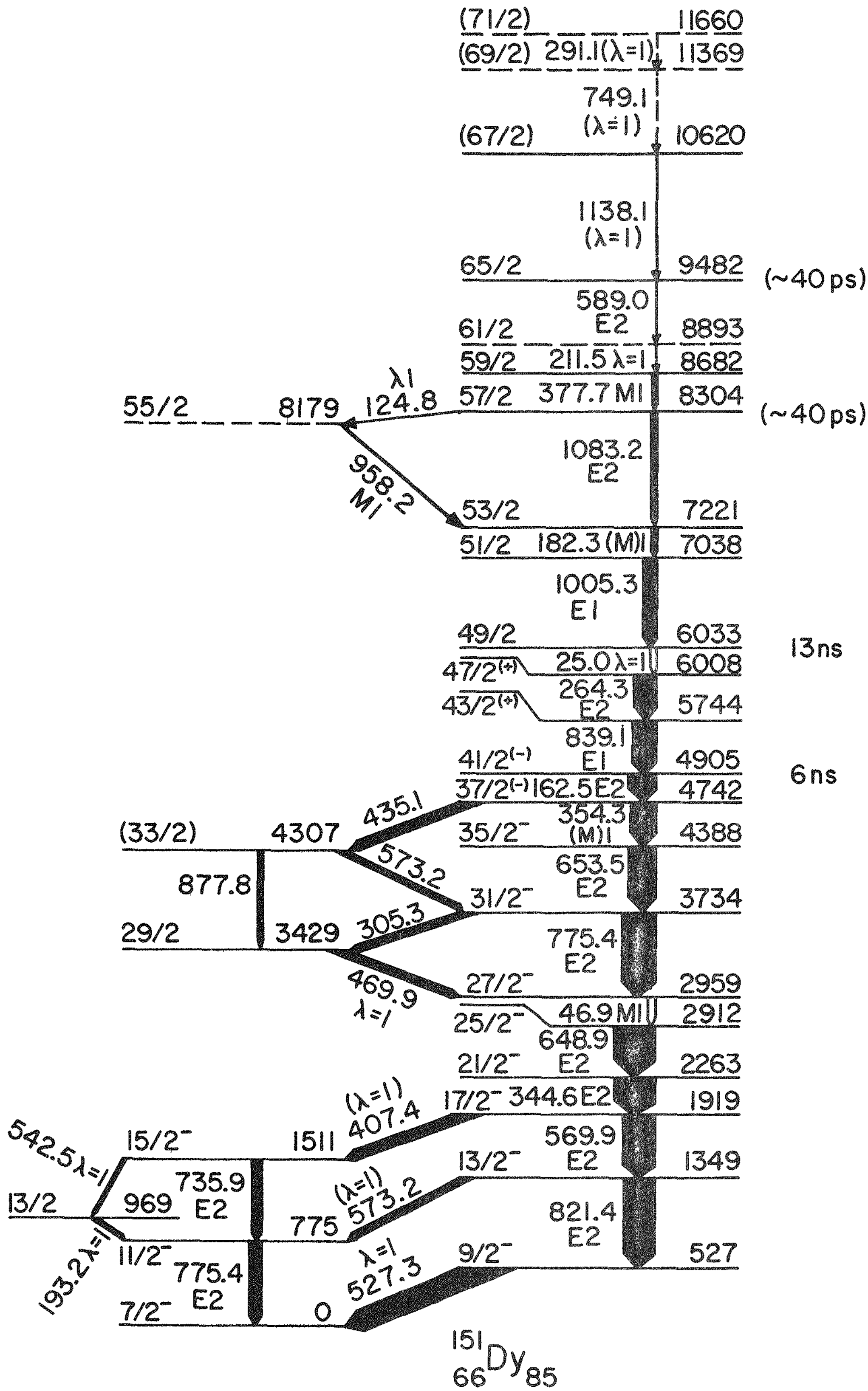

Fig. II-5. Level scheme of ^{151}Dy.

population of the high-spin states is observed with 160-MeV ^{32}S beams; states with I up to 51/2 receive ∿100% of the (^{32}S,5n) reaction strength. This phenomenon, also observed in ^{152}Dy, can probably be attributed to a funneling of the γ excitation via collective transitions—as described in Sec. II.Cd.

d. Unusual Excitation Functions for the Yrast States in ^{152}Dy and ^{151}Dy

R. K. Smither, I. Ahmad,* J. Borggreen, P. Chowdhury, P. J. Daly,† C. L. Dors,† S. R. Faber,† T. L. Khoo, W. Kutschera, and J. Wilson†

The high-spin yrast states in ^{151}Dy and ^{152}Dy were investigated with the reaction $^{122}Sn(^{34}S,xn\gamma)^{151,152}Dy$. The energy of the ^{34}S beam from the Argonne superconducting linac was varied from 144 MeV to 184 MeV in six steps. Excitation curves were taken with a Ge(Li) gamma detector, both in the singles mode and in coincidence with a large NaI sum spectrometer that surrounded the target. Figure II-6 shows the population of yrast states as a function of spin I for the ^{34}S beam energies of 144, 151, 160, 168, and 176 MeV. The relative feeding of these previously determined levels[1] in ^{152}Dy as a function of spin and bombarding energy revealed a normal excitation function for the levels up to the beam energy of 160 MeV with the relative feeding of the highest spin states increasing with increasing beam energy. Above this point, an unusual saturation effect sets in. For $E(^{34}S) \geq 160$ MeV, states with spins of up to 29 ℏ received ∿90% of the $(^{34}S,4n)^{152}Dy$ cross section, with little or no side-feeding below this spin. The population of states with higher spin did not increase even at higher bombarding energies (corresponding to higher angular momentum input). In contrast, a monotonic decrease in population with spin is usually observed in studies on prolate deformed nuclei. The unusual saturation of the high spin population in ^{152}Dy and the results of our continuum measurements suggest that continuum E2 transitions funnel the γ de-excitation into the yrast states at I∿29—38 and away from those at higher spin. A similar behavior in the population of the yrast states of

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[1] T. L. Khoo, R. K. Smither, B. Haas, O. Häusser, H. R. Andrews, D. Horn, and D. Ward, Phys. Rev. Lett. 41, 1027 (1978).

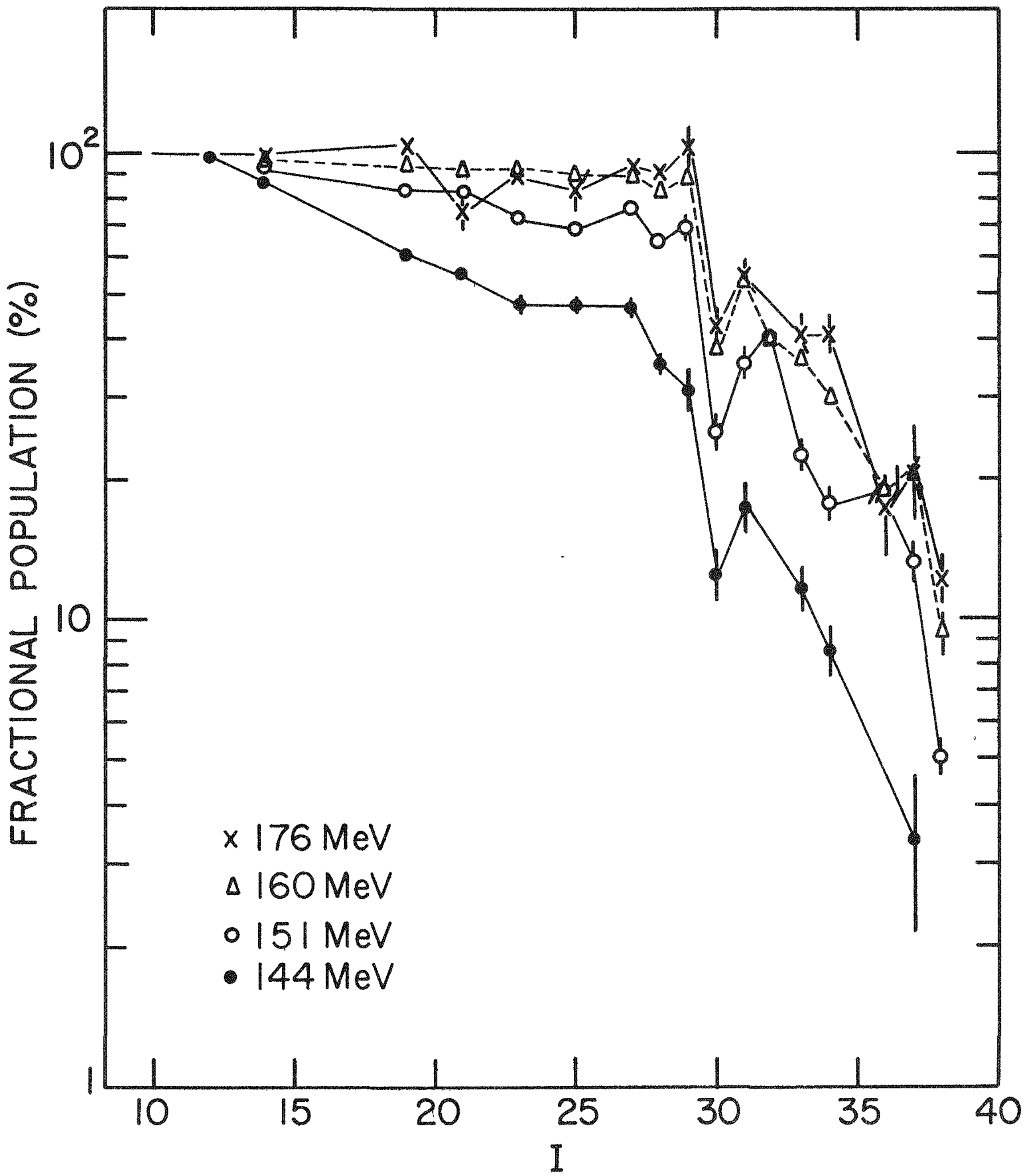

Fig. II-6. Population of yrast states in ^{152}Dy as a function of spin I in the reaction $^{122}Sn(^{34}S,4n)^{152}Dy$ at different bombarding energies. The population is given in percent of the ground-state feeding.

^{151}Dy in the ^{32}S(5n) reaction has also been observed. Further experiments are planned to establish the details of the link between the yrast line and the continuum region (see Sec. II.C.f).

e. Search for Rotational Structures in ^{152}Dy

I. Ahmad,* J. Borggreen, P. Chowdhury, P. J. Daly,† C. L. Dors,† S. R. Faber,† T. L. Khoo, W. Kutschera, R. K. Smither, and J. Wilson†

Our spectroscopic studies of the yrast lines of ^{151,152}Dy suggest that there is a small oblate deformation at high spin. For a sufficiently large deformation, rotational bands will be built on the multiparticle configurations of the yrast line. Even if regular strong-coupled bands do not develop, one might hope to observe the genesis of collective excitations built upon the intrinsic excitations. The stretched E2 continuum transitions we have observed at very high spin would probably feed the yrast states through these collective excitations. Using the ^{124}Sn(^{32}S,4n) and ^{122}Sn(^{34}S,4n) reactions, we have initiated attempts to search for such nonyrast states, using Ge–Ge coincidence techniques. Operation in coincidence with a sum spectrometer makes it possible to improve the detection sensitivity of transitions feeding the yrast states by selecting prompt transitions and by enhancing γ rays in the reaction channel of interest, viz. ^{152}Dy. The short half-lives of these transitions would lead to considerable Doppler broadening for the γ rays as the evaporation residues slow in a stopper; to avoid this problem, the residues were recoiled into vacuum and the γ rays observed at forward angles. Analysis of the data is in progress.

f. Study of Continuum γ-Ray Spectra of ^{151,152}Dy

J. Borggreen, I. Ahmad,* P. Chowdhury, T. L. Khoo, W. Kutschera, R. K. Smither, P. J. Daly,† C. L. Dors,† S. R. Faber,† and J. Wilson†

We have utilized 150- and 162-MeV ^{34}S beams from the Argonne linac to populate states in ^{151,152}Dy in an attempt to determine the relationship between the population of high spin yrast states and the continuum of γ rays feeding these discrete states. We have observed continuum γ rays

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in a 10-in. × 12-in. NaI detector (with a 3-in. diameter central collimator) which were coincident with events in a sum spectrometer. By selecting high sum energy slices, high angular momentum states are enhanced. With this enhancement, the NaI spectra exhibit an enhanced yield around 1.4 MeV, well separated from any known discrete lines. (See Fig. II-7.) Anisotropy measurements of this energy region suggest that it consists of many unresolved stretched quadrupole transitions. These results, together with the excitation functions for the discrete yrast lines imply that the de-excitation of high-ℓ events ($\ell \gtrsim 35\ \hbar$) is not feeding the yrast line directly via statistical transitions, but is diverted by continuum cascades of E2 character, and only reaches the yrast line at $\ell \sim 25$—$30\ \hbar$. The fact that the mean energy of the "bump" remains fairly constant over a large range of incoming ℓ values implies a moment of inertia which seems to increase linearly with spin.

The observed E2 continuum transitions are probably from deformed collective bands which emerge at only high spin (and possibly only at high excitation above the yrast line). An experiment to establish the collectivity of these transitions by lifetime measurements will be very important and will be undertaken.

g. Study of High-Spin Isomers in ^{152}Er

J. Borggreen, I. Ahmad,* P. Chowdhury, P. J. Daly,† C. L. Dors,† S. R. Faber,† T. L. Khoo, W. Kutschera, R. K. Smither, and J. Wilson†

Recent measurements by the Copenhagen-GSI collaboration revealed an island of high-spin isomers at $82 < N < 86$ and $Z \leq 68$. One of these isomers—in ^{152}Er—exhibits an excitation energy as high as $\sim$13 MeV and may have a spin of $\sim 35\ \hbar$. Theoretical studies point out that spherical nuclei in this region may undergo major shape change above spin $\sim 40\ \hbar$, becoming distinctly oblate with an axis ratio of 2:3, and that some of the configurations associated with this shape may be isomeric.

The reaction ^{122}Te(^{34}S,4n)^{152}Er at 165 MeV was used in an attempt to populate the isomer. Delayed γ lines below a 30 ns isomer at $\sim$9-MeV excitation energy are clearly observed and agree with the observations made

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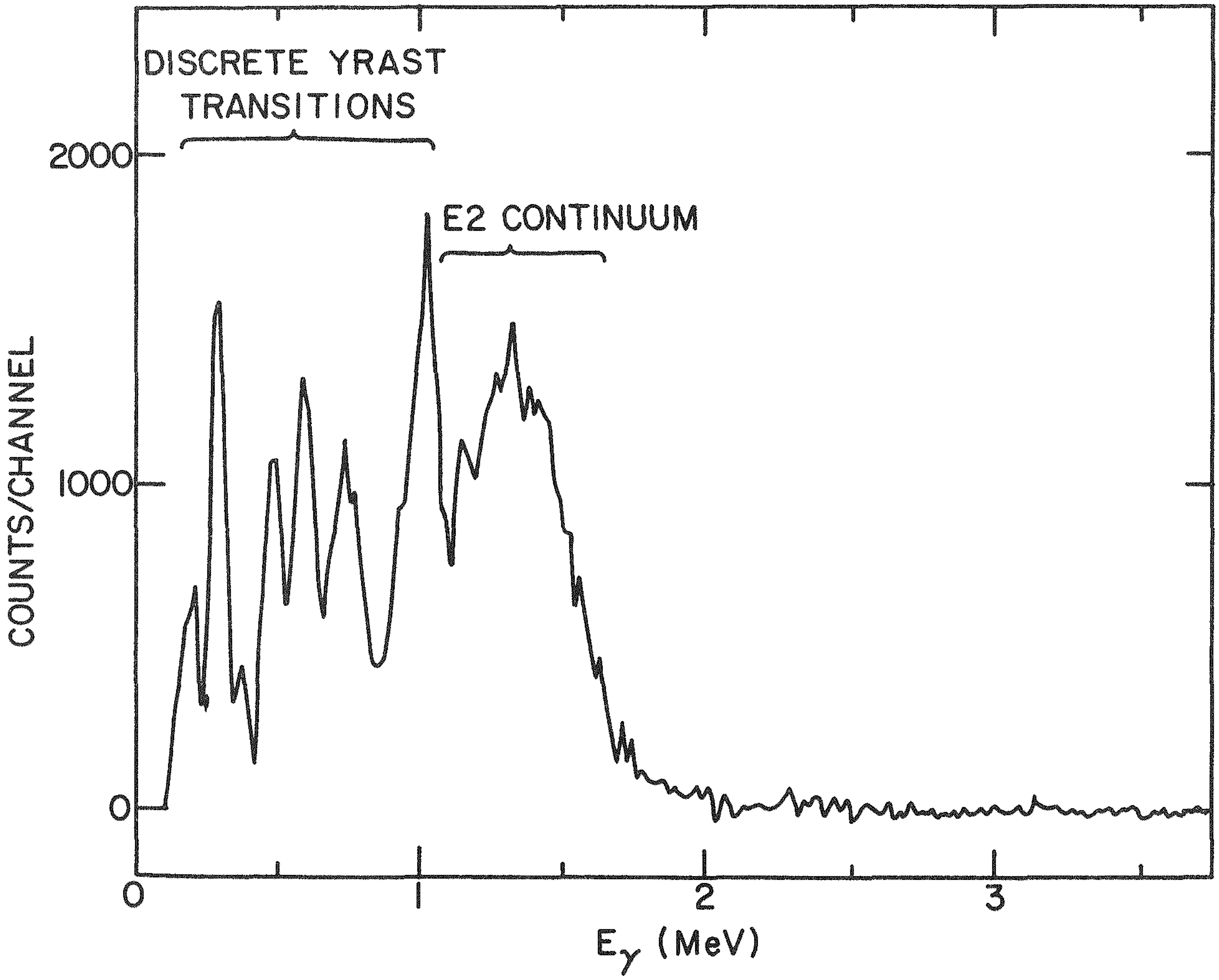

Fig. II-7. Difference between two NaI spectra coincident with a high energy and a low energy sum slice. The two spectra are normalized to the yield of the statistical γ rays above ∿2 MeV.

by other groups. We have delayed γ lines which feed this isomer and which may decay from the 5 ns isomer at 13 MeV. Sorting of the data stored on tape is not finished, the main purpose being to build a decay scheme and to measure spectra of the "expected" band feeding the 5 ns isomer.

D. REACTION MECHANISMS AND DISTRIBUTION OF REACTION STRENGTHS

The study of heavy-ion induced reaction mechanisms and the distribution of reaction strengths has been an ongoing program at the Argonne Physics Division for a number of years. In the past year these studies have been continued by a selective study of single-nucleon transfer near the Coulomb barrier and by a number of measurements at higher energy with beams from the linac. These initial studies at the linac have concentrated on the distribution of quasielastic and strongly-damped reaction strengths as a function of incident energy for medium-heavy systems, a study of the inclusive alpha-particle production of incident ^{16}O ions at energies $E/A \gtrsim 5$ MeV/nucleon and measurements of fusion-fission excitation functions and their mass and kinetic energy distributions.

a. Single-Nucleon Transfer Reactions Induced on ^{48}Ca by ^{12}C Beams at $E_{lab}(^{12}C) = 45$ MeV

J. Petersen,* R. Ascuitto,* D. G. Kovar, S. J. Sanders, W. Henning, and M. Paul

The $^{48}Ca(^{12}C,^{11}B)^{49}Sc$ and $^{48}Ca(^{12}C,^{13}C)^{47}Ca$ transfer reactions leading to low-lying states in the final nuclei were studied at $E_{lab}(^{12}C) = 45$ MeV to investigate the reaction mechanism. Studies have shown that transfer reactions in this mass and energy range cannot, in general, be well described by conventional DWBA calculations.[1] Recently, an effective Q-value model has been proposed which was able to reproduce the angular distribution behaviors observed in single-nucleon transfer induced by ^{16}O on ^{48}Ca.[2] In the present study, we investigated whether the model can successfully describe the results observed in the population of the same final states in transfer reactions induced by another projectile (i.e., ^{12}C). Angular distributions for the $(^{12}C,^{11}B)$ and $(^{12}C,^{13}C)$ transfers were measured using the ANL split-pole magnetic spectrograph with a gas ionization chamber-proportional counter focal plane detector. Shown in Fig. II-8 are the angular distributions obtained for transfers to single-particle (1-hole) states in the final nucleus with the outgoing projectile in the ground state and in an excited state. The solid curves shown are conventional DWBA calculations performed with the code PTOLEMY when the spectroscopic factors obtained from light particle studies are used to give the absolute

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*Yale University, New Haven, Connecticut.

[1] D. G. Kovar *et al.*, Phys. Rev. C 17, 83 (1978).

[2] E. A. Seglie *et al.*, Phys. Rev. Lett. 42, 956 (1979).

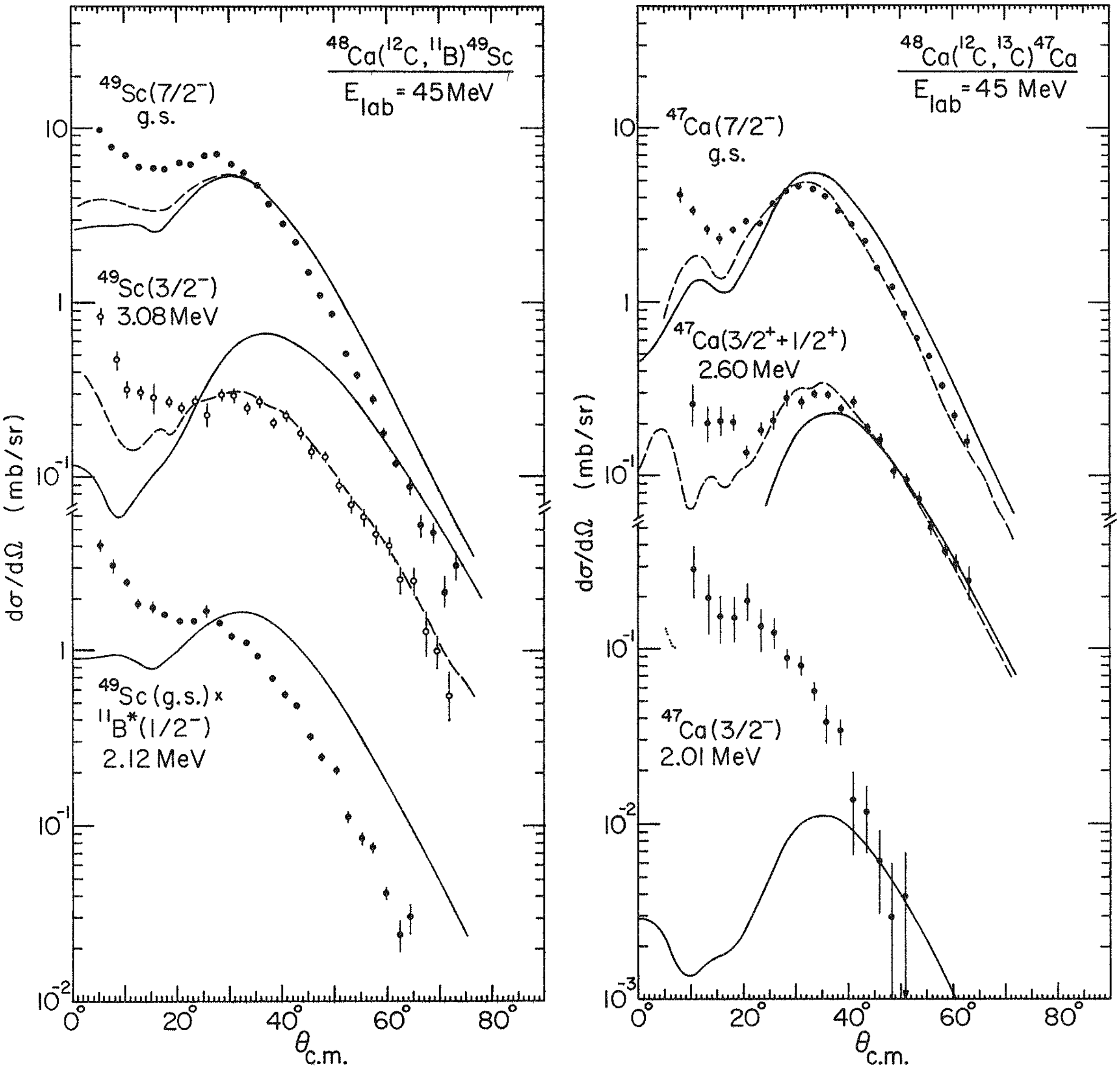

Fig. II-8. Angular distributions obtained for (^{12}C,^{11}B) and (^{12}C,^{13}C) transfers on ^{48}Ca. The solid curves are conventional DWBA calculations and the dotted curves are predictions of the effective Q-value model.

normalization. As can be seen, the calculations poorly reproduce the experimentally observed angular distributions. The dotted curves represent the predictions of the effective Q-value model; while the agreement is better, the behavior at forward angles is still not well reproduced. Further investigations are underway to study dependence of the predictions on the optical model parameters used.

b. Reaction Studies of $^{32}S + ^{40,48}Ca$

D. F. Geesaman, W. Henning, D. G. Kovar, M. Paul, S. J. Sanders, J. P. Schiffer, B. B. Back,* C. Jachcinski, and C. Olmer

The interaction of a ^{32}S beam with targets of ^{40}Ca and ^{48}Ca was studied at incident energies of 143, 170, 198, and 230 MeV. The aim is to measure the cross section of quasielastic and deep-inelastic reaction products over a bombarding energy range that extends from near the Coulomb barrier to well above it. Of particular interest is whether nuclear structure effects become evident in a comparison between the two target nuclei, which differ by a fully filled $f_{7/2}$ neutron shell.

Angular distributions of the quasielastic and deeply-inelastic reaction products were measured with a ΔE-E surface barrier detector telescope. The cross sections are presently being evaluated. One feature that persists to the highest incident energy is the strong odd-even dependence in charge transfer for ^{40}Ca as compared to ^{48}Ca, as evidenced in Fig. II-9 for an energy spectrum slice that corresponds to rather negative ($\approx$ -70 MeV) Q value. This odd-even staggering parallels that of ground-state Q values; it is not yet clear whether it reflects properties of the statistical decay following the reactions or indeed reveals some entrance channel dependence.

c. Reaction Studies of $^{28}Si + ^{24}Mg$

W. Henning, C. Olmer,† M. Paul,‡ and S. J. Sanders

Our resonance studies of ^{16}O induced alpha transfer reactions on ^{24}Mg targets suggest the existence of relatively narrow, high-spin resonances

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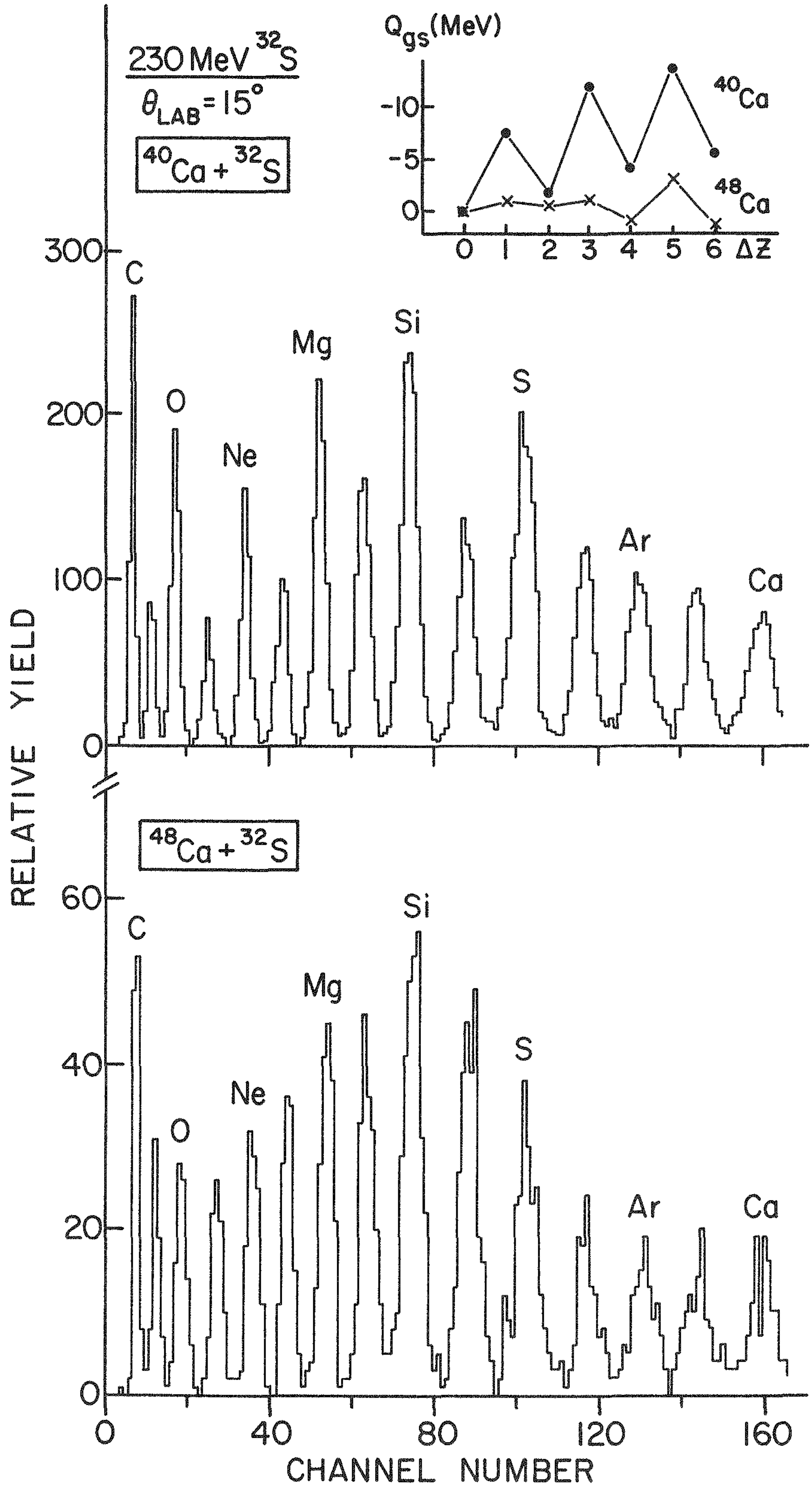

Fig. II-9. Odd-even dependence in charge transfer for ^{40}Ca as compared to ^{48}Ca as seen in an energy slice corresponding to Q ≈ -70 MeV.

at high excitation energy in the ^{40}Ca compound nucleus. With a 170-MeV ^{28}Si beam from the linac we have attempted to further verify the existence of such states in the continuum by direct transfer of an ^{16}O cluster onto the ^{24}Mg target nucleus in the reaction ^{24}Mg(^{28}Si,^{12}C)^{40}Ca. While we observe considerable ^{12}C strength to excitation energies in ^{40}Ca near the expected resonances, no clear structures have yet been identified. For momentum matching reasons it is desirable to perform these measurements at even higher incident energy, which will become possible with the beams from the linac in the near future.

d. Study of the Inclusive Alpha-Particle Yields Produced in the ^{16}O + ^{40}Ca Reaction

D. G. Kovar, C. N. Davids, D. F. Geesaman, M. Paul, F. W. Prosser, Jr.,* R. Racca,* S. J. Sanders, and B. Zeidman

Recent studies of light heavy-ion induced reactions ($10 \leq A_{proj} \leq 20$) at energies $E/A \gtrsim 5$ MeV/nucleon indicate that the emission of energetic light particles (e.g., protons and alpha particles) plays an important role in the reaction mechanism associated with the fusion and deep-inelastic processes. In previous studies at ANL,[1] the distribution of total reaction strength as a function of bombarding energy for the ^{16}O + ^{40}Ca system has been established over the energy range $40 \leq E_{lab}(^{16}O) \leq 214$ MeV, and it was of interest to investigate whether the light particle data together with the previous results might provide an insight into the reaction mechanism. In this investigation, the inclusive alpha-particle yields were measured at $E_{lab}(^{16}O) = 128$ MeV with beams from the linac booster. Using a conventional silicon surface barrier ΔE-E detector telescope, the alpha particles were identified and their angular distributions measured over an angular range $3 \leq \theta_{lab} \leq 150°$. The alpha-particle energy spectra at forward angles showed yields up to a laboratory energy of 60 MeV, well above the energies expected from a compound nucleus evaporation process and indicative of a direct or pre-equilibrium process. At present, these results are being analyzed.

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*University of Kansas, Lawrence, Kansas.

[1] S. E. Vigdor, D. G. Kovar, P. Sperr, J. Mahoney, A. Menchaca-Rocha, C. Olmer, and M. S. Zisman, Phys. Rev. C 20, 2147 (1979).

Further studies are now planned to establish the inclusive alpha-particle yields as function of bombarding energy and to measure the alpha-particle fusion residue coincidences.

e. Heavy-Ion Induced Fusion-Fission

B. Back,* R. Betts,* W. Henning, J. M. Lebowitz,† A. Mignerey,‡ and K. Wolf*

Fission cross sections for the $^{32}S + ^{144,150,152,154}Sm$ systems have been measured from threshold to 230 MeV. The data for $^{32}S + ^{154}Sm$ are shown in Fig. II-10. At energies near threshold, the cross sections for the different isotopes show significant differences as illustrated in the inset, whereas at higher energies, their behavior is quite similar. The results near threshold are similar to those observed in measurements of the fusion of ^{16}O + Sm, namely, the lighter-mass spherical isotopes have the smaller cross sections, an effect which can be traced to the influence of deformation on the interaction barrier. The interest in the present results stems from the implication that these deformation effects persist even at the higher angular momenta ($\sim$20 $\hbar$) of the fission threshold. Further detailed analysis of the higher energy data will enable a mapping of the fission probability as a function of angular momentum and provide a detailed test of liquid drop model predictions of fission barriers at high angular momentum.

f. Fission Mass and Kinetic Energy Distributions of Pt Isotopes Formed by Heavy-Ion Fusion Reactions

B. Glagola,* B. B. Back,* R. R. Betts,* K. E. Wolf,* W. Henning, A. C. Mignerey,‡ and J. M. Lebowitz†

Fission properties of Pt nuclei populated in $^{16}O + ^{170}Yb$ and $^{32}S + ^{144,150,152,154}Sm$ fusion reactions have been studied at the Argonne superconducting linac. Beam energies have been matched in the $^{16}O + ^{170}Yb$ and $^{32}S + ^{154}Sm$ reactions to produce the ^{186}Pt compound system at identical excitation energies in the range from $E^* = 55$—100 MeV in order to separate

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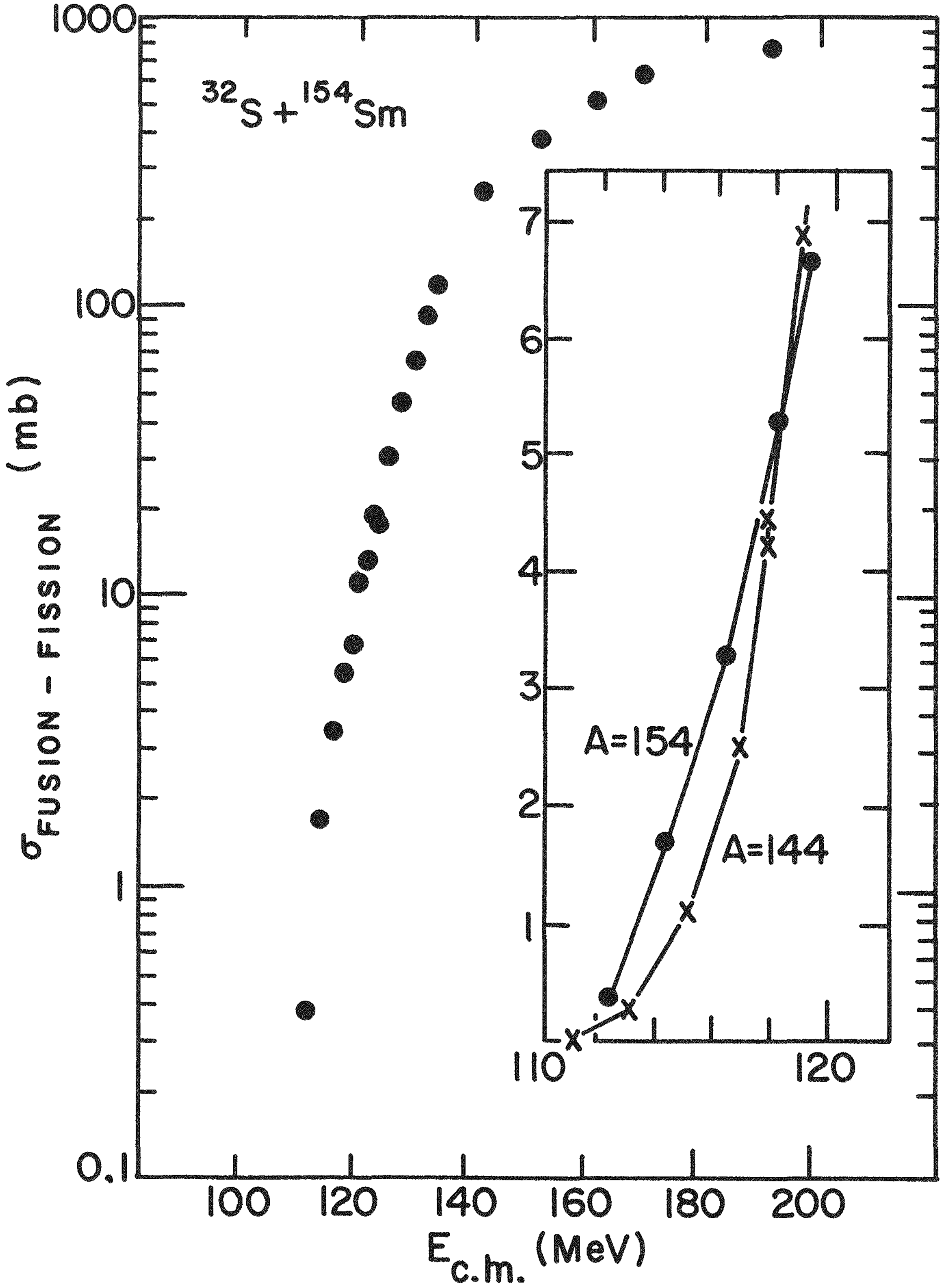

Fig. II-10. Fusion-fission cross sections observed for $^{32}S + ^{144,154}Sm$.

the effects of excitation energy and angular momentum on the fission properties. Fission kinetic energies show a weak dependence on the excitation of the fissioning system, but are not affected by angular momentum. The final analysis is underway.

III. CHARGED-PARTICLE RESEARCH

INTRODUCTION

This program encompasses a broad range of studies centered about the Dynamitron and Tandem Van de Graaff accelerators in the Physics Division. These include studies of nuclear reactions of potential interest in thermonuclear energy generation, the A dependence of Coulomb displacement energies in $f_{7/2}$-shell nuclei, properties of isotopes of interest to explosive nucleosynthesis, laser spectroscopy of radioactive ions, accelerator mass spectrometry, fundamental aspects of weak interactions as evidenced in nuclear-decay processes, and parity violation in specific nuclear levels induced by neutral weak currents.

The charged-particle research program in the Physics Division is carried out by a number of researchers in the Division. A very substantial interaction with researchers in the university community is also involved. The charged-particle research uses both the Dynamitron (25% of available time) and the FN Tandem accelerator (25% of available time).

A. CHARGED-PARTICLE RESEARCH AT THE DYNAMITRON

This program has two principal components. One is primarily concerned with the study of various properties of the weak interaction at low energies in light nuclei. The major effort at present is to measure the presence of the neutral current (predicted by the renormalizable electro-weak theory) in the hadron-hadron interaction via the detection of parity violation in ^{10}B. A major emphasis over the next two years will be the further investigation of the symmetries of the hadronic weak current through model-independent studies of beta decay properties in light nuclei. This will include tests of CVC in A = 12 (beta spectrum shape measurements) and A = 8 [$^{4}He(\alpha,\gamma)$ measurement]. Another subject of interest is the presence of meson exchange corrections to the nuclear weak current, particularly the axial vector current. One measurement [$^{16}N(0^-) \rightarrow {}^{16}O(0^+)$ β decay] is currently planned to study this effect. The second component is the ongoing investigation of exothermic reactions with light nuclei at energies below a few MeV. The reactions to be studied are selected on the basis of their interest to nuclear physics, astrophysics, and/or their potential use in fusion energy. For example, absolute cross sections for two reactions basic to a possible ^{6}Li-H fuel cycle have recently been measured. An experiment to measure the very small low-energy cross section of the $^{4}He(^{3}He,\gamma)^{7}Be$ reaction—of current importance in nuclear astrophysics—is being planned.

1. WEAK INTERACTIONS

a. Parity Violation in the 5.1-MeV J=2 Doublet of ^{10}B

C. A. Gagliardi,* S. J. Freedman,† T. J. Bowles, A. R. Davis,‡ G. T. Garvey, R. D. McKeown, B. Myslek-Laurikainen, and R. G. H. Robertson

Since the discovery of the neutral weak current, there has been a great deal of experimental interest in defining its nature. To date, all of the semileptonic results are well described by the SU(2)×U(1) gauge theory of Weinberg-Salam with mixing angle $\sin^2\theta_w \sim 0.2$—0.25. Meanwhile, studies of the purely hadronic neutral current have been more ambiguous.

The only method available for studying the hadronic weak current is to measure parity-violating effects. Thus, it is natural to describe it in terms of parity-violating amplitudes of definite isospin. When CP

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invariance is included, one finds that only the $\Delta T=1$ component can have a one-pion exchange contribution.

The $\Delta T=0$ and 2 currents arise from the exchange of multiple pions and heavier mesons, causing the associated parity-violating forces to have much shorter range. This makes results of calculations of the $\Delta T=0$ and $\Delta T=2$ effects highly model dependent because they depend on the repulsive core of the nucleon-nucleon force which is only poorly understood.

In addition to the fact that the $\Delta T=1$ case is unencumbered by these theoretical uncertainties, the Cabibbo (charged) current contribution for $\Delta T = 1$ is suppressed by a factor $\sin^2\theta_c$ relative to the neutral current. It is thus natural to attempt to observe the neutral weak current by studying cases of pure $\Delta T=1$ parity violation.

Despite intensive efforts, previous experiments to measure pure $\Delta T=1$ parity violation have merely set an upper limit on the size of the effect. We have undertaken a study of $\Delta T=1$ parity violation in ^{10}B by measuring mixing between the 2^+ T=1 state at 5.16 MeV and the 2^- T=0 state at 5.11 MeV. The 2^+ T=1 state is produced via the $^6\vec{Li}(\alpha,\gamma)^{10}B$ reaction, using a 1.2-MeV α beam from the Argonne Dynamitron. The total cross section is given by

$$\sigma = \sigma_0(1 + \tfrac{1}{2} P_{zz} + FP_z),$$

where the z axis is along the α-beam direction. The quantity of interest is F, the helicity dependence of the rate.

The polarized ^6Li target for the experiment is complete. An intense ^6Li atomic beam is produced by an oven with a large bore orifice. The oven holds 700 gm of ^6Li and is capable of running $\sim$1 week at 850°C without refilling. The beam is collimated and then polarized using a pair of large gap (1.2 cm diameter), high field ($\sim$12.5 kG) sextupole magnets. Figure III-1 shows this part of the apparatus. The atomic polarization is converted to nuclear polarization using a weak-field rf-transition unit. Atomic beam fluxes of $\gtrsim 2 \times 10^{16}$ atoms/cm^2-sec and nuclear polarizations of $\sim$0.6 have been observed. The $^6\vec{Li}$ impinges on a hot ($\sim$1100°C) oxidized tungsten surface in a holding field. The sitting time is such as to provide a monolayer target to a 50—100-μA α beam with almost no depolarization. Subsequent γ decays are observed using a cylindrical NaI detector with a solid angle close to 4π.

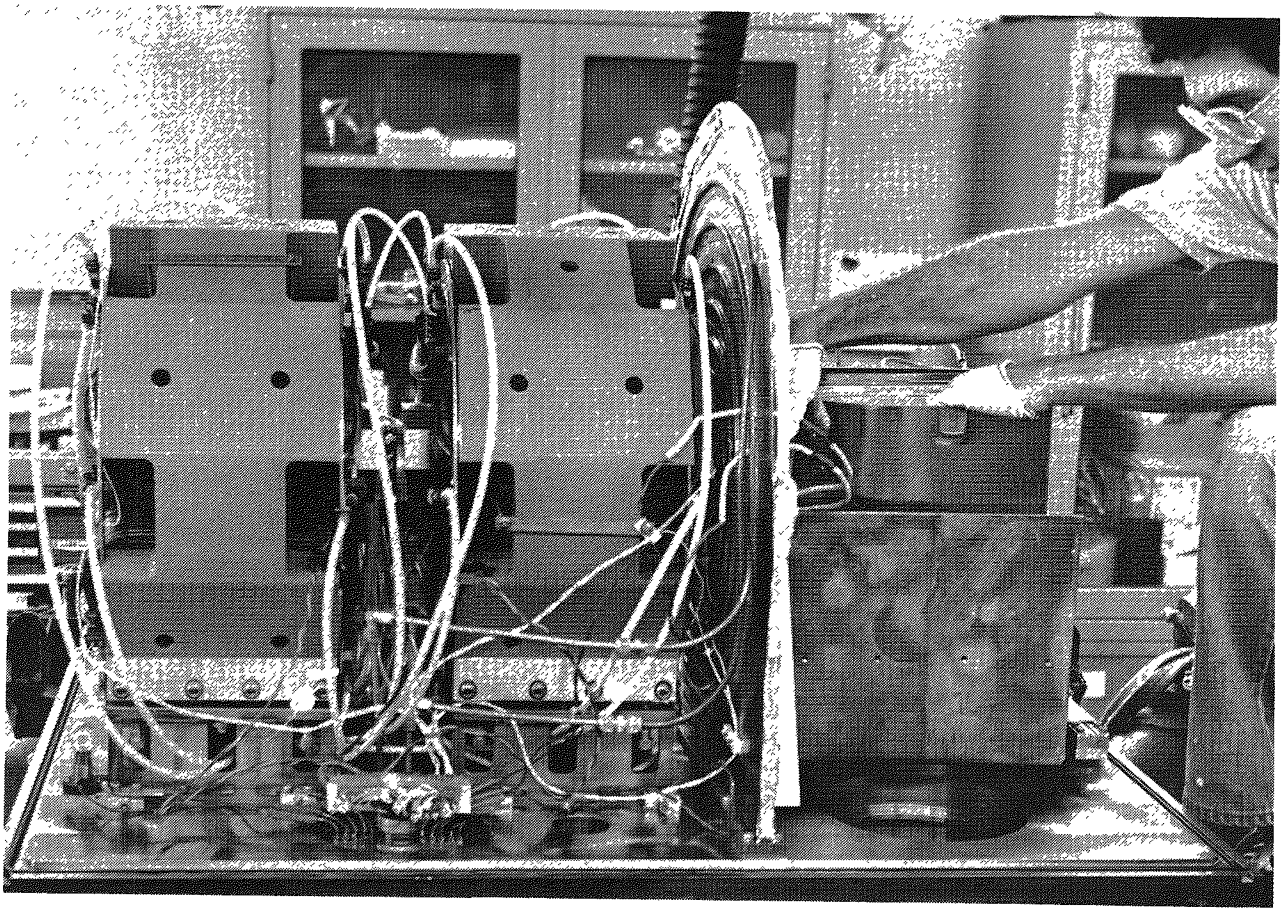

Fig. III-1. View of the ^{6}Li atomic beam apparatus with the vacuum chamber top removed. On the right are the lithium and radiation shields for the oven. On the left are the sextupole magnets which polarize and focus the atomic beam.

The atomic beam will be moved to the Dynamitron in June 1980 and data taking for the $^{6}\vec{Li}(\alpha,\gamma)^{10}B$ reaction should begin in August 1980.

b. Search for Neutral Currents in ^{6}Li

R. G. H. Robertson, T. J. Bowles, P. Dyer,* R. C. Melin,* A. B. McDonald,† G. C. Ball,† W. G. Davies,† and E. D. Earle†

The α-d breakup of the 0^{+} T=1 state at 3.56 MeV in ^{6}Li is forbidden by both parity and isospin conservation. If the decay occurs, it signifies the presence of a 0^{-} T=0 component. Admixture of such a component is greatly inhibited if only conventional charged weak currents exist, but may not be

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suppressed if there is in addition a hadronic weak neutral current of the type postulated by Weinberg and Salam.

The decay is being measured via the inverse reaction $^{2}H(\alpha,\gamma)^{6}Li$ using a QDDD spectrometer and stopping gas proportional counter to identify the recoiling ^{6}Li ions at 0°. The target is a supersonic deuterium gas jet. In an initial experiment at Chalk River, an upper limit on the parity-violating alpha width two orders of magnitude lower than the best previous experiment was achieved. It is expected that, if the experiment is continued for one month's running time, a significant upper limit on the neutral current "enhancement" could be obtained.

c. $^{16}N(0^-) \rightarrow {}^{16}O(0^+)$ Beta Decay

R. D. McKeown, G. T. Garvey, C. A. Gagliardi,* and S. J. Freedman†

The 0^- state at 120 keV in ^{16}N predominantly gamma decays to the 2^- ground state, but has a very small ($\sim 3 \times 10^{-6}$) branching ratio for β decay to the ^{16}O ground state. The inverse muon capture rate (Λ_μ) for $\mu^- + {}^{16}O \rightarrow {}^{16}N(0^-) + \nu_\mu$ has been measured to ∿10% accuracy. The only successful measurement of the beta decay rate (Λ_β) resulted in a value with ∿25% accuracy.

The ratio $\Lambda_\mu/\Lambda_\beta$ has been the subject of much recent theoretical interest. There are three basic issues involved in the interpretation of $\Lambda_\mu/\Lambda_\beta$: (a) the contribution of meson exchange currents, (b) the value of g_p (pseudoscalar form factor in the nucleon weak current) in nuclear matter, and (c) the q^2 dependence of form factors in the elementary particle approach. The theoretical investigations indicate that a more accurate measurement of Λ_β would be very useful.

The availability of intense deuteron beams from the Dynamitron [^{16}N is formed via the $^{15}N(d,p)$ reaction] enables a measurement of Λ_β with higher statistical accuracy. Several target designs are under consideration, and a preliminary run is planned to further assess the feasibility of the measurement.

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d. Measurement of the T=2 Level in ^{24}Al

R. G. H. Robertson, T. J. Bowles, A. G. Ledebuhr,* and L. Harwood*

A cryogenic (liquid-nitrogen cooled) helium jet system has been constructed and used at Michigan State University to observe the highly proton-rich nucleus ^{24}Si (also recently observed at Berkeley[1]). A precise measurement of the energy of β-delayed protons from the T=2 state in the daughter ^{24}Al has yielded a test of the isobaric multiplet mass equation as stringent as any made. Only in mass 9 has this level of accuracy been obtained, and there a substantial deviation from the quadratic IMME is found. In mass 24, however, there is no indication of significant disagreement with the equation.

2. CROSS SECTIONS—ASTROPHYSICS

a. Cross Sections for the ^{6}Li(p,^{3}He)^{4}He Reaction at Low Energies

A. J. Elwyn, R. E. Holland, C. N. Davids, L. Meyer-Schützmeister,
F. P. Mooring, and W. J. Ray, Jr.

As part of our continuing program to measure absolute cross sections for the reaction of light ions with ^{6}Li at low energies, we have completed the study of the ^{6}Li(p,^{3}He)^{4}He reaction, and a paper has recently appeared in the Physical Review.[2] Differential and total cross sections at proton energies between 0.14 and 3.0 MeV have been obtained, and the results comprise a consistent set of data over an energy range of interest to studies of nuclear structure in the mass 7 system, as well as to applications for fusion reactions based on the use of advanced fuels.

Further study of light-ion interactions with ^{6}Li will concentrate on completing experiments on the determination of the cross sections for elastic deuteron scattering. Elastic scattering measurements involving protons, ^{3}He, and α particles, which are of interest to fusion-energy applications, will be considered. At the same time other low-energy light-ion reactions that offer the possibility of illuminating certain specific aspects of nuclear structure or nuclear astrophysics are being planned.

*Michigan State University, East Lansing, Michigan.

[1] J. Äystö, D. M. Moltz, M. D. Cable, R. D. von Dincklage, R. F. Parry, J. M. Wouters, and Joseph Cerny, Phys. Lett. 82B, 43 (1979).

[2] A. J. Elwyn, R. E. Holland, C. N. Davids, L. Meyer-Schützmeister, F. P. Mooring, and W. Ray, Jr., Phys. Rev. C 20, 1984 (1979).

b. The $^{6}Li(^{3}He,p)$ Reaction at Low Energy

R. E. Holland, A. J. Elwyn, C. N. Davids, F. P. Mooring, J. E. Monahan, and W. J. Ray, Jr.

Nuclear reactions of ^{3}He with ^{6}Li are important contributors to thermonuclear reaction rates associated with the p-^{6}Li advanced fuel cycle. We have recently completed cross-section measurements for $^{3}He + {}^{6}Li \rightarrow 2\,{}^{4}He + p$ reactions at energies between 0.5 and 1.85 MeV. Pulsed ^{3}He beams from the Dynamitron accelerator along with time-of-flight techniques were used to study separately the yields for outgoing protons, α particles, and in some instances, deuterons. Differential and total cross sections for the protons associated with the ground, 2.94-, 16.63-, and 16.92-MeV states in ^{8}Be, as well as for the underlying continuum protons that arise from various 3-body breakup mechanisms, were obtained to absolute accuracies of between 10 and 20%. The total cross sections, which are plotted in Fig. III-2, represent a much more complete and systematic determination of cross sections in the energy region below 2 MeV than do previously published measurements. Thermonuclear reaction rates calculated from the measured cross sections suggest that the total reactivity in the p-^{6}Li fuel cycle may be considerably larger than previous studies have indicated.

c. $^{4}He(^{3}He,\gamma)^{7}Be$ and the Solar Neutrino Problem

B. W. Filippone,* C. N. Davids, A. J. Elwyn, and R. E. Holland

A new experiment is under way to measure the total cross section for radiative capture of ^{3}He on ^{4}He. The rate of this reaction appears to be one of the weakest links in the chain of nuclear reactions postulated to take place in the center of the sun. Observations of the weakly interacting neutrinos emanating from the sun probe these nuclear reactions in the solar interior. Experimental measurements and theoretical calculations of the neutrino rate currently differ by a factor of three. There are indications that low-energy extrapolations of nuclear cross sections [particularly for the $^{4}He(^{3}He,\gamma)^{7}Be$ reaction] may be at fault. This is the motivation for the present experiment.

While previous studies of this reaction have used the capture γ rays to determine the cross section, we intend to use an independent method:

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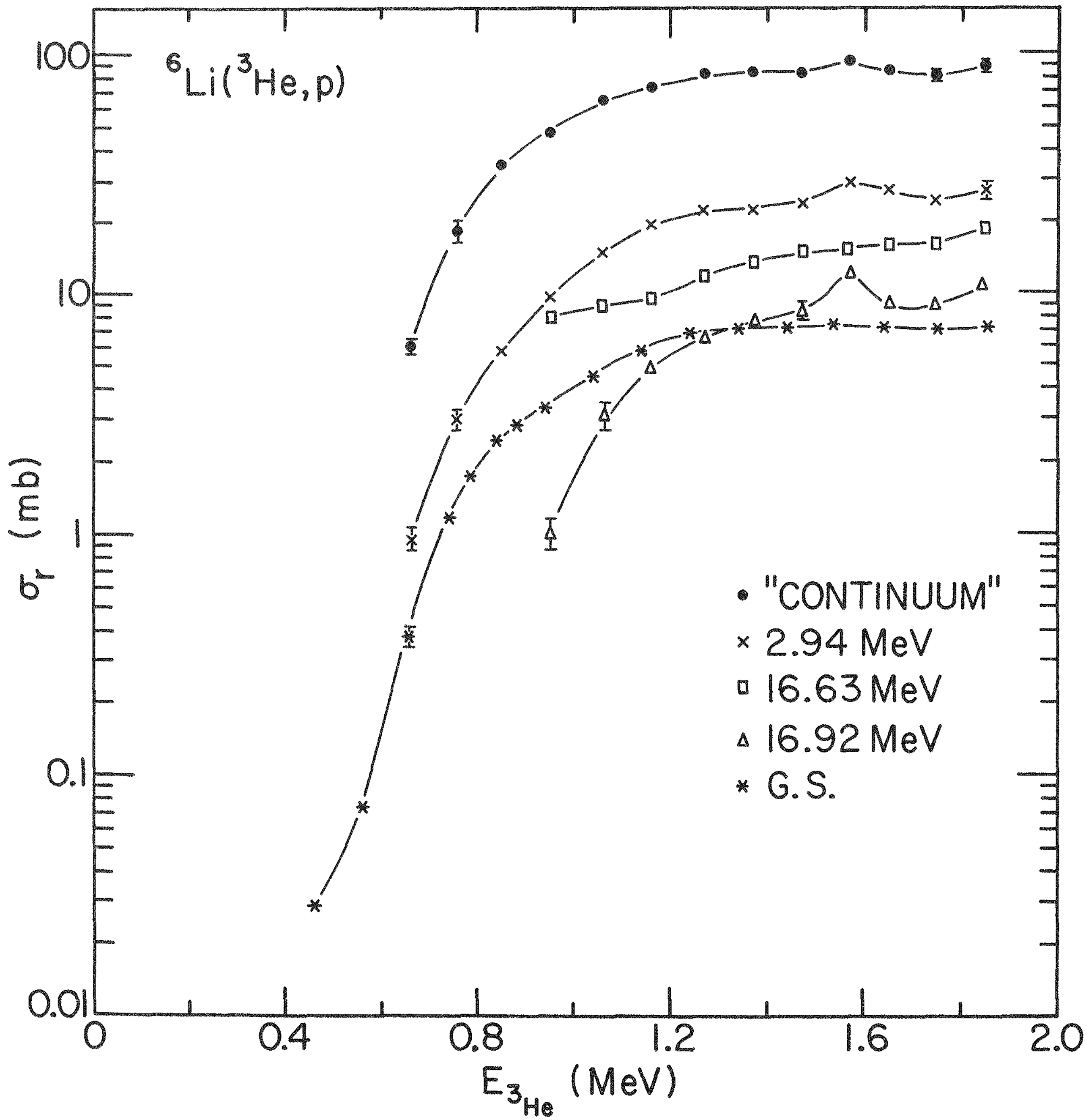

Fig. III-2. Total cross sections for the reaction ^{6}Li(^{3}He,p) to states in ^{8}Be and to the "continuum." The "continuum" cross section represents contributions from simultaneous three-body breakup as well as decay through ^{5}Li and a possible state in ^{8}Be at 11.4 MeV. (None of these processes gives rise to readily identifiable peaks.) The relative errors of these cross sections are shown by the vertical error bars when the relative errors are larger than the symbol on the figure. Total errors include an additional contribution of between 8 and 15 percent for estimated systematic errors.

counting the recoiling of ^{7}Be. This is to be accomplished by catching the recoils in a foil and observing the γ rays following electron capture decay of the ^{7}Be (half-life = 53 days) in a low background counting station. A windowless supersonic jet He target is under construction, to be used in conjunction with the 4-MV Dynamitron accelerator for this study.

Using the $^{6}Li(d,n)^{7}Be$ reaction, which has a very large cross section, preliminary measurements have been made on the ability of certain foils to retain the ^{7}Be. These indicate that water-cooled Au catcher foils can hold the ^{7}Be even under heavy bombardment. We are also continuing investigation of low background systems for improved sensitivity.

3. FURTHER ATTEMPTS TO SEARCH FOR STABLE FRACTIONALLY-CHARGED PARTICLES IN GASES

A. R. Davis,* W. Kutschera, S. M. Levenson,* R. D. McKeown, F. P. Mooring, and J. P. Schiffer

In view of continuing reports from Stanford University on the observation of fractional ($+\frac{1}{3}$ e and $-\frac{1}{3}$ e) charges on superconducting Nb spheres, we have attempted to extend earlier Argonne searches, in which no such charges were seen. We attempted to sample various gases (He, N_2, and O_2) by accelerating any charged particles in these gases in the Dynamitron, allowing them to pass through a thin foil (to dissociate complex molecules that could cause difficulties), then analyzing them in a purely electrostatic system, and finally measuring the energy of such particles in a semiconductor detector. This technique had been used previously at Argonne to set limits on the concentration of $+\frac{1}{3}$ e particles in Nb, W, and Fe metal. The experiment was unsuccessful, because of difficulties in the initial extraction of charged particles. The normal rf ion source for gases was used but with the rf power turned off. However, the extraction field in an rf ion source depends critically on the configuration taken on by the plasma induced by the rf discharge and shaped by the dc probe voltage. In the absence of such a discharge, the extraction efficiency from an rf bottle is likely to be very substantially reduced, and without major modification the method is not likely to be reliable for setting limits on fractional charges in gases.

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*Thesis student, University of Chicago, Chicago, Illinois.

B. CHARGED-PARTICLE RESEARCH AT THE TANDEM ACCELERATOR

Two new areas of investigation have recently been initiated at the tandem. One is the laser spectroscopy of radioactive atoms (in collaboration with researchers from the University of Minnesota and Iowa State University). The second is an application of techniques of accelerator mass spectrometry for radioisotope dating and other nuclear physics measurements. The study of nuclei far from stability is proceeding. This program has concentrated on the production and study of isotopes of interest to explosive nucleosynthesis. Both proton- and neutron-rich isotopes near iron have been investigated. Masses, β-decay rates, and spectroscopic information have been obtained for a large number of nuclides using β- and γ-ray spectroscopy. Also continuing is the study of low-lying levels of the proton-rich $T=\frac{1}{2}$ nuclei in the 2p-1f shell. When compared with the neutron-rich member of the multiplet, interesting state-dependent Coulomb-energy shifts are seen in these spectra.

1. $f_{7/2}$ NUCLEI

a. Gamma-Ray Studies in ^{45}V

S. A. Gronemeyer,* L. Meyer-Schützmeister, G. Hardie, and A. J. Elwyn

We have been studying the A dependence of Coulomb displacement energies in $f_{7/2}$-shell nuclei. In particular we have determined these energies by comparing the level structure of $T=\frac{1}{2}$ mirror pairs. As part of this program an intensive investigation of ^{45}V was made since its mirror, ^{45}Ti, is well known. The gamma decay of ^{45}V was investigated using the $^{40}Ca(^{7}Li,2n)^{45}V$ reaction with ^{7}Li beams in the energy range 14—16 MeV. Prompt and delayed neutron-gamma and gamma-gamma coincidences were measured. The following level scheme has been established: $7/2^-$(g.s.), $5/2^-$(56.4 keV), $3/2^-$(57.2 keV), $3/2^+$(386.1 keV), $5/2^+$(796.8 keV), and $7/2^+$(1273 keV). In addition, half-lives were measured for the $5/2^-$ state at 56.4 keV($\lesssim$4.2 nsec) and the $3/2^-$ state at 57.2 keV (430 ± 80 nsec). Comparison of the ^{45}V level structure with that of its mirror nucleus, ^{45}Ti, permitted the extraction of Coulomb displacement energies for both natural and unnatural parity states in the A=45 system. A paper with the above title has been published.[1]

*Thesis student, Washington University, St. Louis, Missouri.

[1] S. A. Gronemeyer, L. Meyer-Schützmeister, A. J. Elwyn, and G. Hardie, Phys. Rev. C 21, 1290 (1980).

b. The Beta Decay of ^{45}V

G. Hardie, S. A. Gronemeyer,* L. Meyer-Schützmeister, A. J. Elwyn, and C. N. Davids

As part of our investigation of ^{45}V, we have attempted to study its superallowed beta decay to the ground state of ^{45}Ti (^{45}V—^{45}Ti form a T=½ pair). A measurement of the half-life for this decay would permit the extraction of the Gamow-Teller (GT) matrix element which is of interest since it is sensitive to the nucleon configurations of the states involved. Since mirror nuclei often decay strongly to excited states in the daughter nuclei, we also searched for a GT branch to the $5/2^-$ state (E_x = 40 keV) in ^{45}Ti. The latter investigation was conducted using the $^{40}Ca(^7Li,2n)$ reaction, which is the process most suitable for studying the level structure of ^{45}V. It was possible to set an upper limit of about 12% on a branch to the $5/2^-$ state.

The $(^7Li,2n)$ reaction unfortunately could not be used to measure the beta-decay half-life of ^{45}V because of the possibility of producing ^{46}V which has a beta end-point energy very close to that of ^{45}V. Hence we were forced to use the $^{40}Ca(^6Li,n)$ reaction which produces ^{45}V with a cross section even lower than the $^{40}Ca(^7Li,2n)$ reaction. Our preliminary experiments yield a half-life of 410 ± 50 msec which yields $|M_{GT}| = 0.79 \pm 0.10$. This matrix element is substantially smaller than the single-particle value ($|M_{GT}| = 1.134$) indicating significant configuration mixing in the $f_{7/2}$ ground state. Because of various uncertainties in the measurements, any conclusions must be considered highly tentative.

c. Coulomb Shifts of T=½ Mirror Nuclei in the $f_{7/2}$ Shell

L. Meyer-Schützmeister, G. Hardie, S. A. Gronemeyer,* and A. J. Elwyn

In continuation of our program in which T=½ mirror nuclei in the $f_{7/2}$ shell are studied, we have observed that the Coulomb shifts, ΔE_c, exhibit a linear A dependence for the natural parity states $7/2^-$ and $5/2^-$, while the unnatural parity states with spins $3/2^+$, $5/2^+$, and $7/2^+$ show a more complicated A dependence. The $3/2^+$ states, for example, have ΔE_c values which are larger than those of the $7/2^-$ states by 163, 189, and 213 keV for A = 43, 47, 51 (A = 4n + 3 series nuclei), respectively; but for A = 41 and 45 (A = 4n + 1), the differences are only 86 and 56 keV, respectively.

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For both mass series the $3/2^+$ states are formed by promoting a $d_{3/2}$ nucleon into the $f_{7/2}$ shell, but in case of 4n + 3 series nuclei, this promotion results in a $(f_{7/2})^{4m}$ core with T = 0, $J^\pi = 0^+$, while in the 4n + 1 series a $(f_{7/2})^{4m+2}$ core with T = 1, $J^\pi = 0^+$ is produced. Thus, each member of the mirror pair exhibits either $d_{3/2}$-proton or $d_{3/2}$-neutron promotion in the 4n + 3 series, while each member of the 4n + 1 series shows promotion of both components. On the basis of these assumptions the Coulomb interaction ε of a $d_{3/2}$ proton hole with an $f_{7/2}$ proton can be derived for each mirror pair in both mass series from the measured ΔE_c values. The deduced ε values increase smoothly (within experimental error) from -290 keV for A = 51 to -190 for A = 41. Although this change of ε is not yet understood, it is consistent with the assumption that the $f_{7/2}$ charge radius increases slightly with A.

2. STUDY OF RADIOACTIVE NUCLEI

a. The β^+ Decay of ^{67}As

M. J. Murphy,* C. N. Davids, and E. B. Norman*

We have completed a study of the new isotope $^{67}_{33}$As ($T_{1/2}$ = 42.5 ± 1.2 s). It was produced via the reaction ^{58}Ni(^{14}N,αn)^{67}As. Singles γ, and γ-γ and β^+-γ coincidences were used to obtain the half-life, decay scheme, and mass excess. The observed log ft values, in conjunction with the known spins of six states in the daughter ^{67}Ge fed in the β^+ decay, constrain the ground-state spin of ^{67}As to be $3/2^-$ or $5/2^-$. The decay scheme obtained for ^{67}As is shown in Fig. III-3. Figure III-4 shows the β^+ spectrum in coincidence with the 120.8 and 243.6-keV γ rays that was used to obtain the total decay energy Q_{EC} for ^{67}As. This number and the mass excess of ^{67}Ge recently measured in this laboratory yields a value of -56.65 ± 0.10 MeV for the ^{67}As mass excess. When compared to various mass predictions, this result is in better agreement with those based on shell-model systematics than with liquid drop models.

The spins of the odd-A As isotopes for A ≥ 73 are all $3/2^-$, while both ^{71}As and ^{69}As have spin $5/2^-$. Since the pairing of 2 $f_{5/2}$ protons is most likely responsible for the 3/2 spin of the heavier isotopes, the fact

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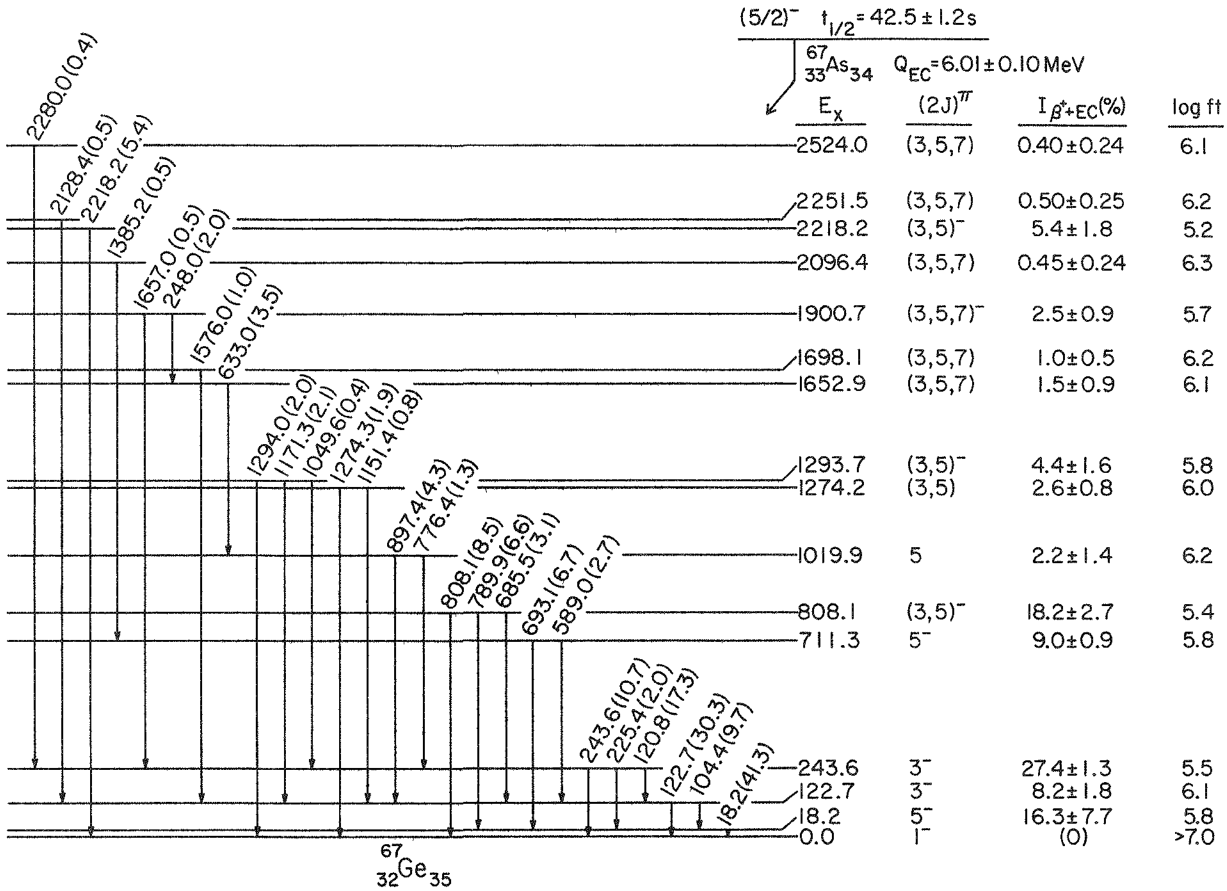

Fig. III-3. Decay scheme for ^{67}As.

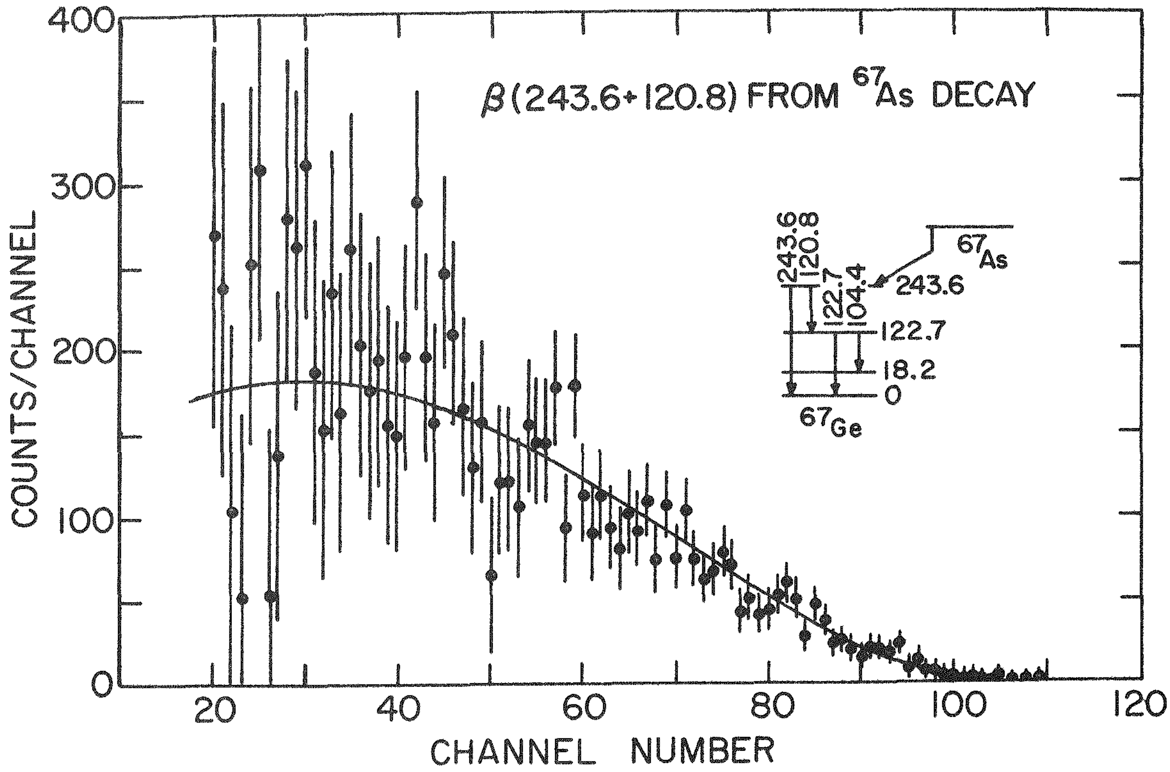

Fig. III-4. β^+ spectrum in coincidence with 243.6- and 120.8-keV γ rays from ^{67}As decay.

that the lighter isotopes have spin 5/2 indicates a weakening of this effect as neutron number decreases. This strongly suggests a spin of $5/2^-$ for ^{67}As, but the data do not allow a clear choice between 5/2 or 3/2.

b. The Structure of ^{67}Ge and Its Relationship to Other 1f-2p Shell Nuclei

M. J. Murphy* and C. N. Davids

A detailed investigation, via gamma-ray spectroscopy, of the level structure and gamma decay of ^{67}Ge has been completed. Thirty-five excited states have been identified, and spin assignments have been made to the ground state ($\frac{1}{2}^-$) and six excited states on the basis of gamma-ray angular distributions and γ-γ directional correlations. These measurements also provided E2/M1 mixing ratios for seven gamma transitions. Table III-I gives the mixing ratios and the ^{67}Ge level scheme is shown in Fig. III-5.

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TABLE III-I. The ^{67}Ge spins and multipole mixing ratios, from the combined results of the angular distributions and directional correlations.

E_γ	E_i^*	E_f^*	I_i	I_f	Multipolarity	δ
104.4	122.7	18.2	$3/2^-$	$5/2^-$	M1/E2	>4
120.8	243.6	122.7	$3/2^-$	$3/2^-$	M1/E2	<-4.9
122.7	122.7	0	$3/2^-$	$1/2^-$	M1/E2	$0^{+0.18}_{-0.18}$
						$-1.7^{+0.4}_{-0.6}$
243.6	243.6	0	$3/2^-$	$1/2^-$	M1/E2	$0.04^{+0.16}_{-0.16}$
						$-1.7^{+0.6}_{-1.0}$
589.0	711.3	122.7	$5/2^-$	$3/2^-$	M1/E2	$-1.1^{+0.6}_{-2.3}$
734.0	752.2	18.2	$9/2^+$	$5/2^-$	M2	. . .
897.5	1019.9	122.7	5/2	$3/2^-$	M1/E2 E1/M2	$-0.95^{+0.85}_{-2.45}$

The newly-determined characteristics of the lowest excited states of ^{67}Ge, when compared to the corresponding level schemes for ^{63,65}Ni, ^{65,67}Zn, and ^{69}Ge, indicate that all six nuclei share a common structure at low excitation. It has been suggested that, e.g., ^{69}Ge excited states consist of an $f_{5/2}$ or $g_{9/2}$ neutron weakly coupled to vibrational states of ^{68}Ge. However, the absence of any correlation between the ground-state deformation of ^{65,67,69}Zn and that of their core nuclei ^{64,66,68}Zn argues against an interpretation of these odd-A Ni, Zn, and Ge isotopes as single neutrons coupled to vibrational and/or deformed cores. The deformations are shown in Fig. III-6. The data are instead consistent with shell effects arising from the reconfiguration of several valence neutrons coupled to a deformed core.

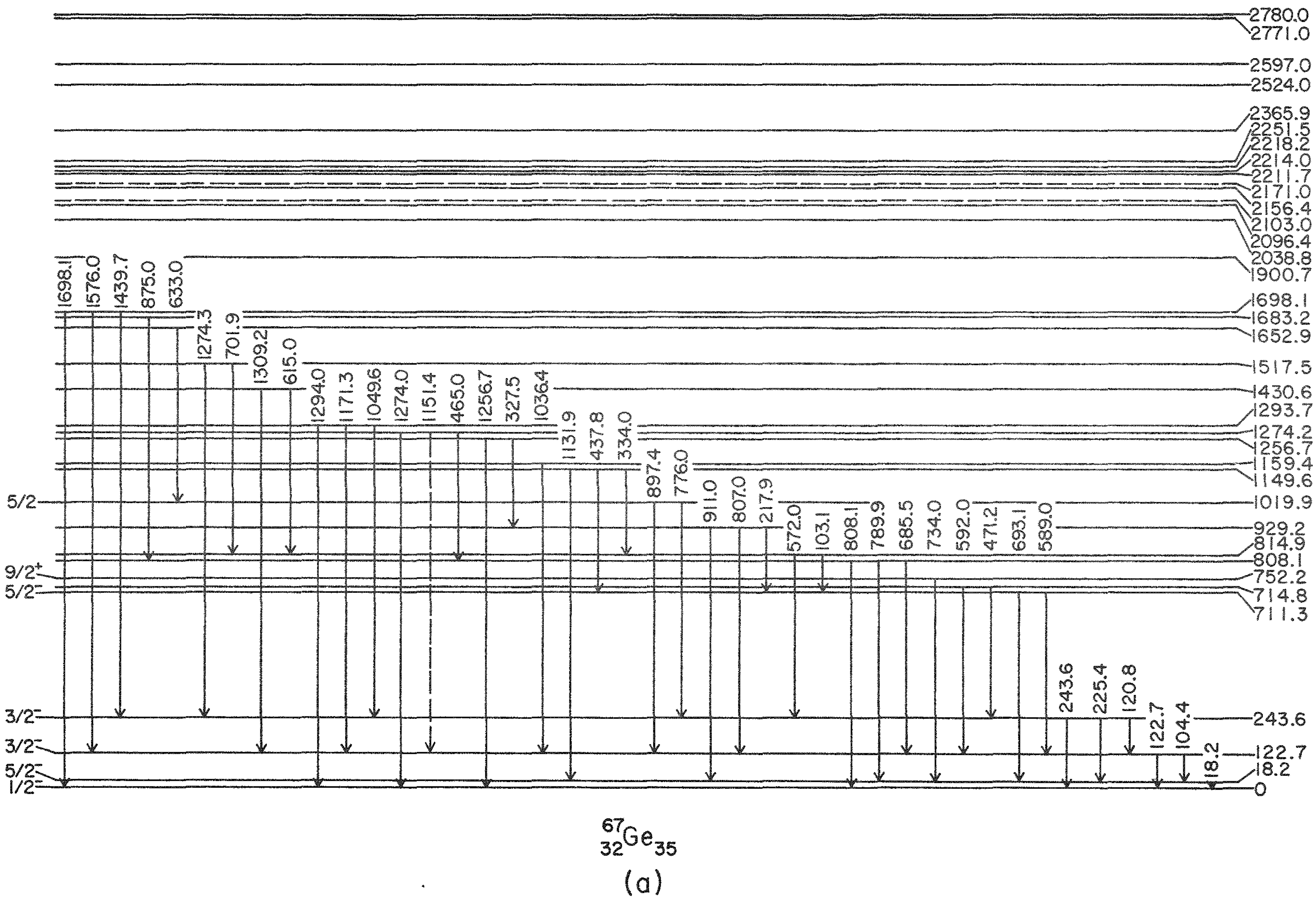
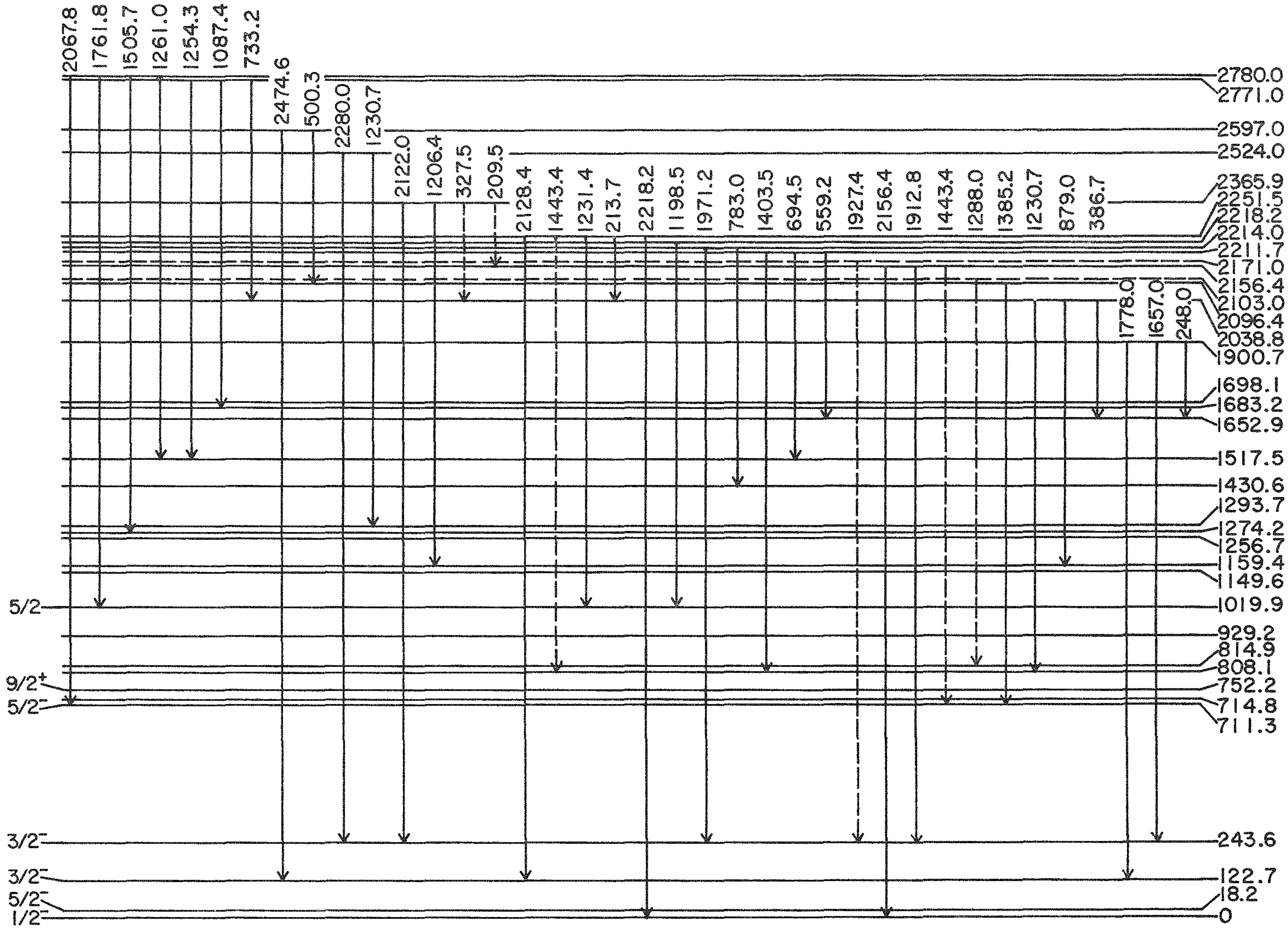


Fig. III-5. Level scheme of ^{67}Ge.



$^{67}_{32}Ge_{35}$

(b)

[Level scheme of ^{67}Ge (cont'd.)]

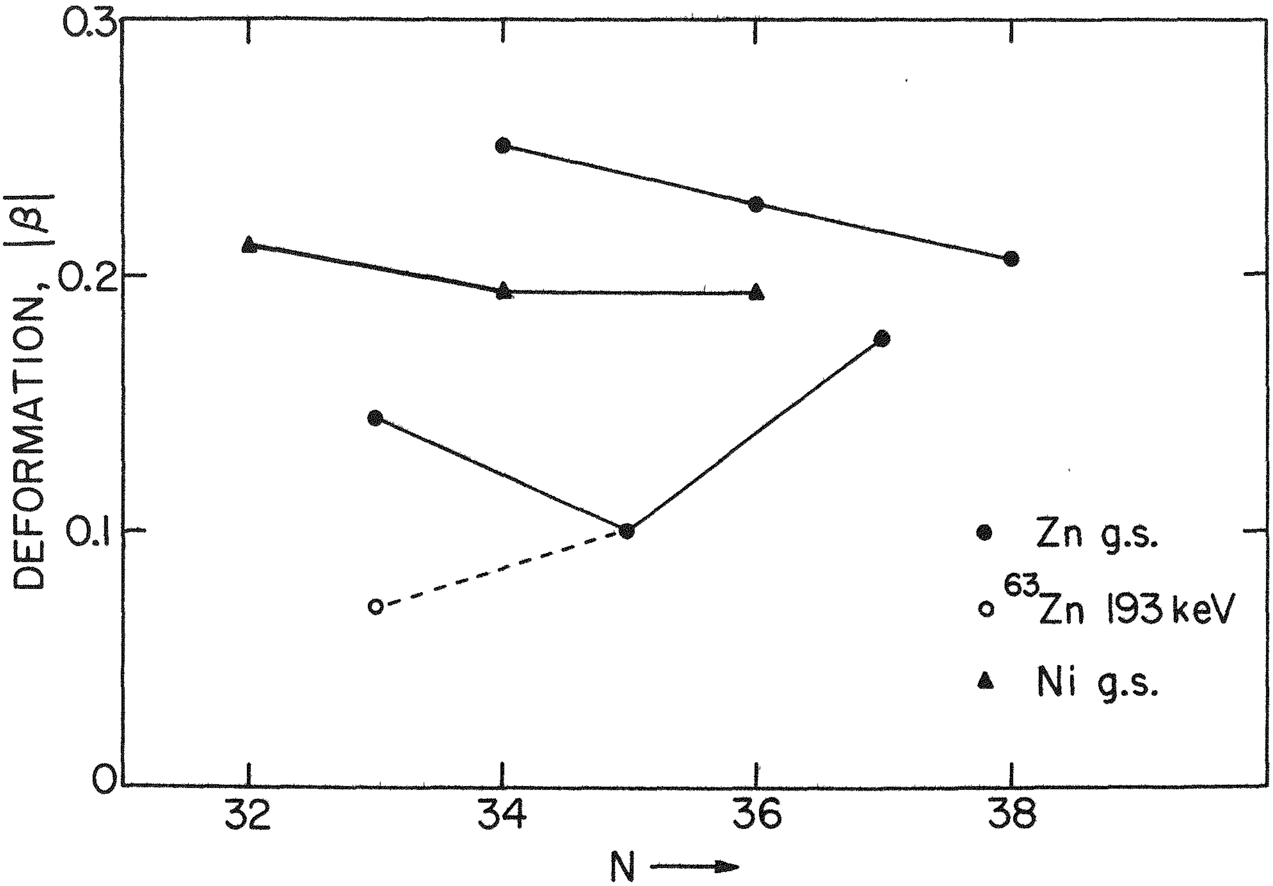


Fig. III-6. Deformations for Zn and Ni isotopes for $32 \leq N \leq 38$.

c. Helium-Jet Recoil Transfer System

C. N. Davids, D. F. Geesaman, W. Kutschera, M. J. Murphy,* and B. Filippone*

Chemical effects have been observed in the transfer of radioactive nuclides through a capillary by helium gas. A small amount of water vapor is normally added to the helium to promote the formation of large clusters under the action of the accelerator beam. The radioactive nuclei recoiling from the target into the helium are stopped and are thought to attach to clusters which are then swept through the capillary. It was noticed that following the bombardment of ^{58}Ni by 48-MeV ^{16}O ions, the intensity of radioactive ^{72}Br observed at the capillary end on a paper collector was much less than that expected from previous results using a rabbit system.

It was thought that the majority of the bromine was not being attached to clusters; instead, it was somehow becoming volatile and being pumped away with the helium. To test this hypothesis a filter consisting of 3μ-pore size filter paper was installed in the capillary between the target and the detector station. No radioactivities at all were delivered to the detector station, indicating that the clusters were being held up in the filter. A small tube containing activated charcoal was then placed in the capillary after the filter, with a detector adjoining it. A high intensity of ^{72}Br decay γ rays was immediately observed. Figure III-7 shows the spectrum obtained. This indicates that the volatile Br activities were passing through the filter and subsequently being trapped by charcoal. The possible form of this activity is HBr, with the hydrogen coming from decomposed water molecules.

Further development of this technique to separate volatile species is expected in the coming year.

d. Decay of ^{72m}Br

C. N. Davids, D. F. Geesaman, W. Kutschera, and M. J. Murphy*

An isomer with a half-life of 10.9 ± 0.1 s has been observed in the β^+ decay of ^{72}Br. Identification of this isomer, which decays by emission of a 101.0 ± 0.2 keV γ ray, and by positron emission, was confirmed by separating bromine isotopes in the helium-jet recoil transport system. Conversion electron measurements show that the 101-keV γ ray is an E2 transition. The yield of delayed γ rays following the positron decay indicates

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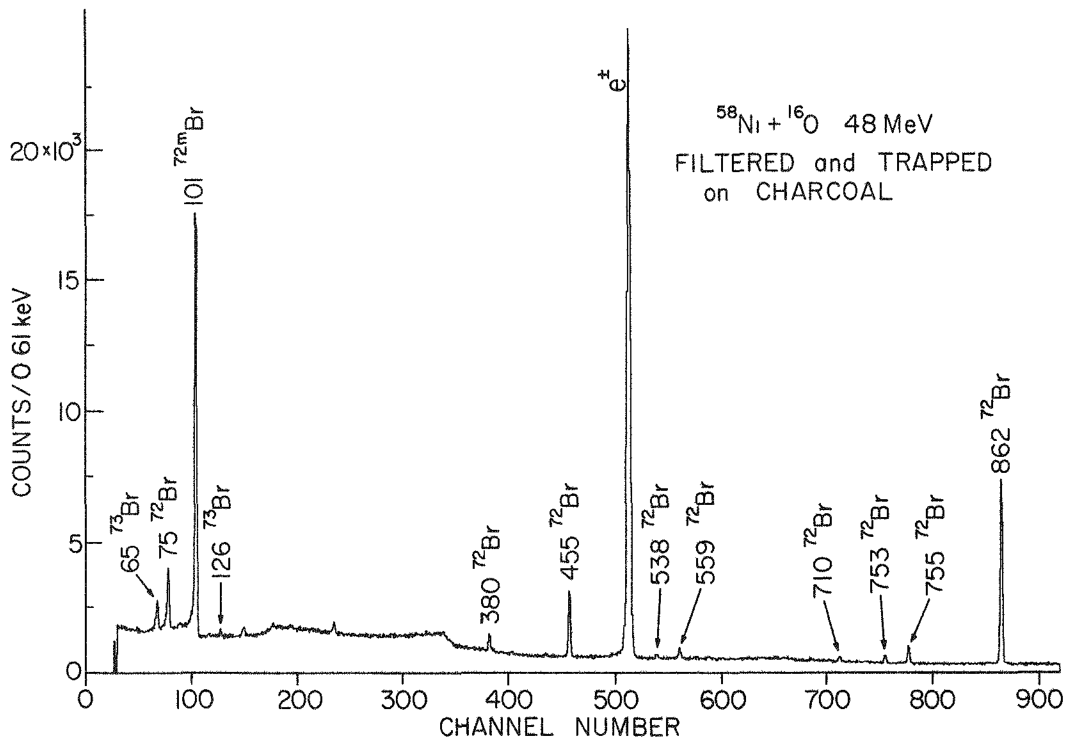
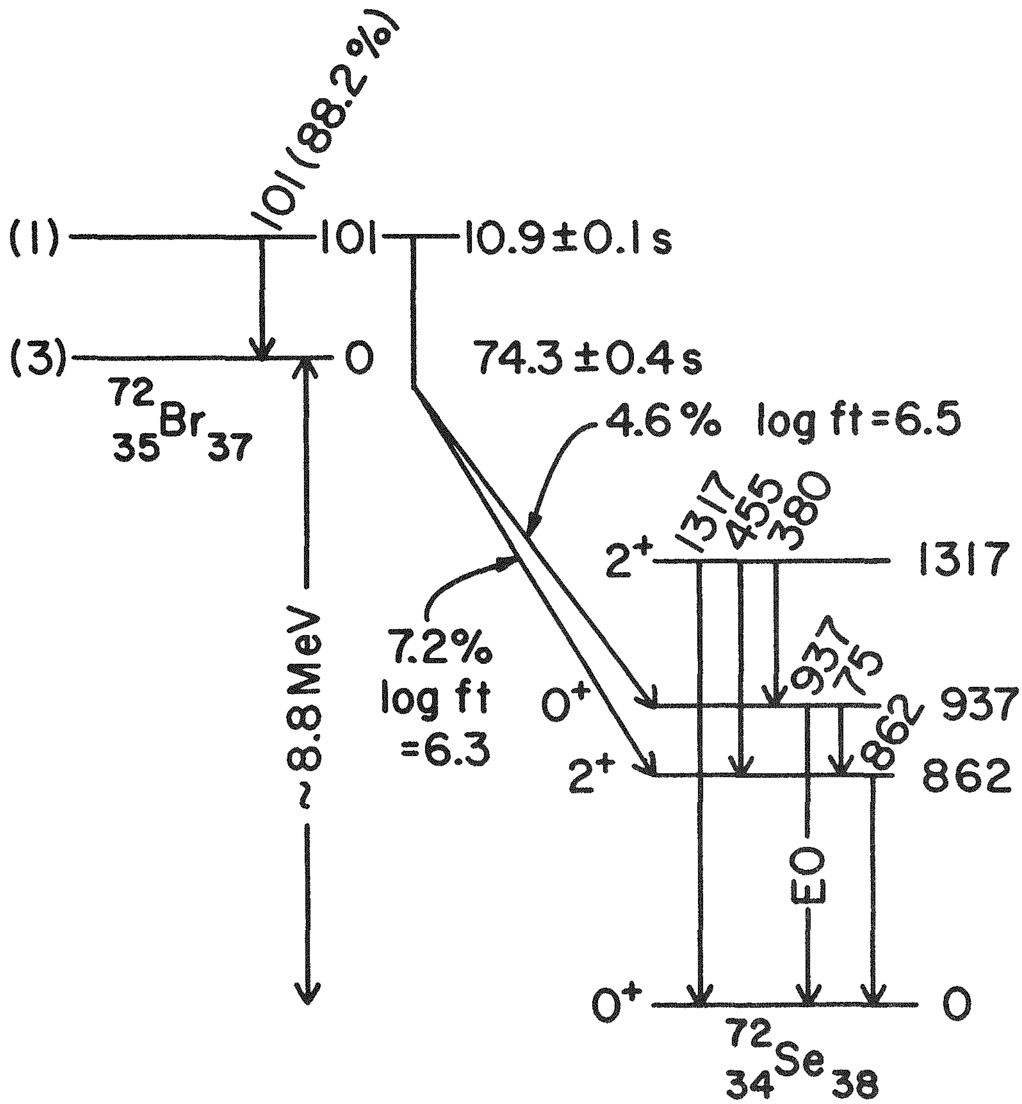


Fig. III-7. γ spectrum following decay of ^{72m}Br.



$\alpha_{101} = 0.93 \pm 0.09$

E2 0.85
M2 1.17

IF E2, 2.4×10^{-7} W.U.

Fig. III-8. Decay scheme of ^{72m}Br.

that the isomer feeds states of spin 0^+ and 2^+ in the daughter nucleus ^{72}Se. Based on the log ft values observed, the isomer thus has spin 1. A decay scheme is shown in Fig. III-8.

Further work is necessary in order to understand the large inhibition observed for the 101-keV transition rate.

e. Laser Spectroscopy of Radioactive Atoms

C. N. Davids, G. Greenlees,* and D. Lewis†

The aim of this new project is the measurement of isotope shifts and hyperfine structure of optical transitions in the atomic spectra of radioactive atoms. Such measurements on a series of isotopes yield detailed information about the changes in the radial behavior of the nuclear charge distribution between isotopes, and allow accurate determination of nuclear electric and magnetic moments.

To obtain Doppler-free fluorescence spectra with the high-resolution tunable CW dye laser, it has usually been the practice to put the species under study in a highly-collimated atomic beam. Since this is impractical for short-lived radioactive isotopes, the experiments planned for the heavy-ion booster will utilize a pure helium-jet recoil transfer system cooled to liquid nitrogen temperature. The cooling will allow free atoms to be transported through the capillary to the laser interaction chamber.

The first measurements are planned on neutron-deficient barium isotopes, to be produced via the Sn(^{12}C,xn)Ba reactions. Currently the cryogenic helium jet system is under design at ANL, and the laser system is being assembled at Iowa State University. A new laboratory will be built at ANL for the measurements.

f. Nuclear Systematics and the Gravitational Collapse of Stars

Martin J. Murphy‡

The gross nuclear systematics derived from studies of exotic, β-unstable nuclei play a fundamental role in models of the gravitational collapse of massive stars. As part of an investigation of this subject, a

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calculation has been made of the equation of state for the core of such a star as it rapidly contracts toward nuclear density. During this phase the core comprises free nucleons and discrete nuclei up to $Z \sim 35$. It has been shown that through electron capture the core can evolve neutron-rich nuclei as far as the edge of the line of stability, and possibly beyond this point in the presence of degenerate neutrons. It has also been found that the nuclei are not compressed, nor does their partition of states begin to involve contributions from the continuum, until nuclear density is reached. Nuclear excitation reduces the adiabatic index of the gas, with its greatest effect occurring at temperatures between 1 and 5 MeV. Throughout the rapid (prenuclear density) phase of collapse, the core composition is dominated by bound nuclei, and its adiabatic index remains $\lesssim 4/3$. Therefore the star will not "bounce back" from its infall during this period.

3. ACCELERATOR MASS SPECTROMETRY

The highly sensitive technique of identifying and counting individual ions in an accelerator beam, recently developed for radioisotope dating, can be conveniently used to determine nuclear quantities of interest when their measurement involves very low radioisotope concentrations. At Argonne, measurements of this type are performed using a spectrometer system with the following major components: an inverted Cs-beam sputter source, the Argonne 9-MV FN tandem accelerator and an Enge split-pole magnetic spectrograph equipped with an ionization-type focal plane detector (Fig. III-9).

First the technique was developed by measuring radioisotope-to-stable isotope ratios in the range of 10^{-8} to 10^{-14} for samples of known radioisotope content,[1] including ^{14}C($T_{1/2}$ = 5730 yr), ^{26}Al(7.2 × 10^5 yr), ^{32}Si(60—710 yr), and ^{36}Cl(3.1 × 10^5 yr). The accelerator values agreed in general within 10—15% with the expected ratio values. The technique has now been applied to measure the half-life of ^{32}Si and cross sections of the $^{26}Mg(p,n)^{26g}Al$ (7.2 × 10^5 yr) reaction near threshold. In a first experiment the method has been recently extended to include the superconducting linac.

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[1] W. Kutschera, W. Henning, M. Paul, E. J. Stephenson, and J. L. Yntema, Radiocarbon (in press).

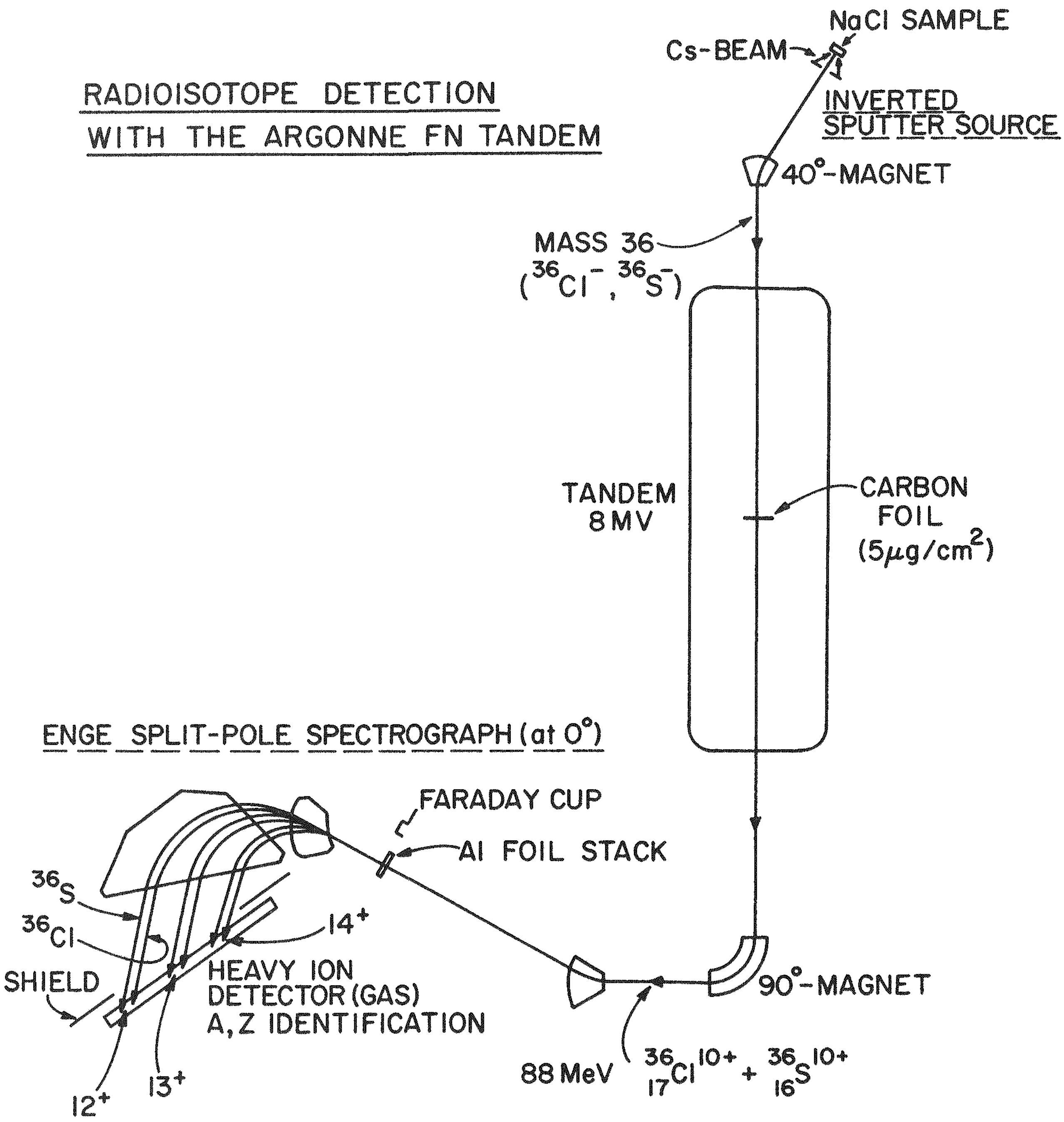

Fig. III-9. Schematic illustration of a ^{36}Cl measurement with the radioisotope detection system at Argonne. The isobaric components ^{36}Cl and ^{36}S are dispersed in energy by the 1.5 mg/cm^2 Al foil stack and hence split up into two components of different magnetic rigidity.

a. Measurement of the ^{32}Si Half-Life

W. Kutschera, W. Henning, M. Paul, R. K. Smither, E. J. Stephenson, J. L. Yntema, D. E. Alburger,* J. B. Cumming,* and G. Harbottle*

In the past, various indirect methods of determining the half-life of ^{32}Si yielded values in the range from 60 to 710 yr, with a most probable value around 300 yr. We have measured the half-life via the relation

$$T_{1/2} = \frac{N}{dN/dt} \ln 2,$$

where N, the number of ^{32}Si nuclei in a sample material prepared through the $^{30}Si(t,p)^{32}Si$ reaction, was measured by accelerator mass spectrometry and dN/dt, the β-disintegration rate, was measured by liquid scintillation technique. Figures III-10 and III-11 illustrate the separation of ^{32}Si ions from a strong omnipresent ^{32}S background. From a $^{32}Si/Si$ ratio of $(2.82 \pm 0.50) \times 10^{-8}$ and a specific β activity of 8250 ± 500 dpm/mg Si, the half-life of ^{32}Si was found to be $T_{1/2} = 96 \pm 18$ yr, considerably shorter than the previously accepted value of approximately 300 yr. We expect that this new value will influence for example results of cosmic-ray flux studies of cosmogenic ^{32}Si in terrestrial, meteoritic and lunar material.

b. Cross Sections of the $^{26}Mg(p,n)^{26g}Al$ (7.2×10^5 yr) Reaction

M. Paul, W. Henning, W. Kutschera, E. J. Stephenson, and J. L. Yntema

The production of primordial ^{26}Al has recently gained great interest, since an excess of its decay product ^{26}Mg was found in certain inclusions of the Allende meteorite,[1] which suggests that ^{26}Al was present in early condensates of the solar system. Prediction for the primordial ^{26}Al concentration in stellar matter depends among other things on the nuclear cross sections of the relevant reactions. A poorly known reaction in this context is $^{26g}Al(n,p)^{26}Mg$, which can be studied via the inverse reaction $^{26}Mg(p,n)^{26g}Al$. We have measured cross sections of this reaction in the astrophysically interesting energy range $E^p_{c.m.} = 5.0$—6.7 MeV.

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*Brookhaven National Laboratory, Upton, New York.

[1] T. Lee, D. A. Papanastassion, and G. J. Wasserburg, Astrophys. J. 211, L107 (1977).

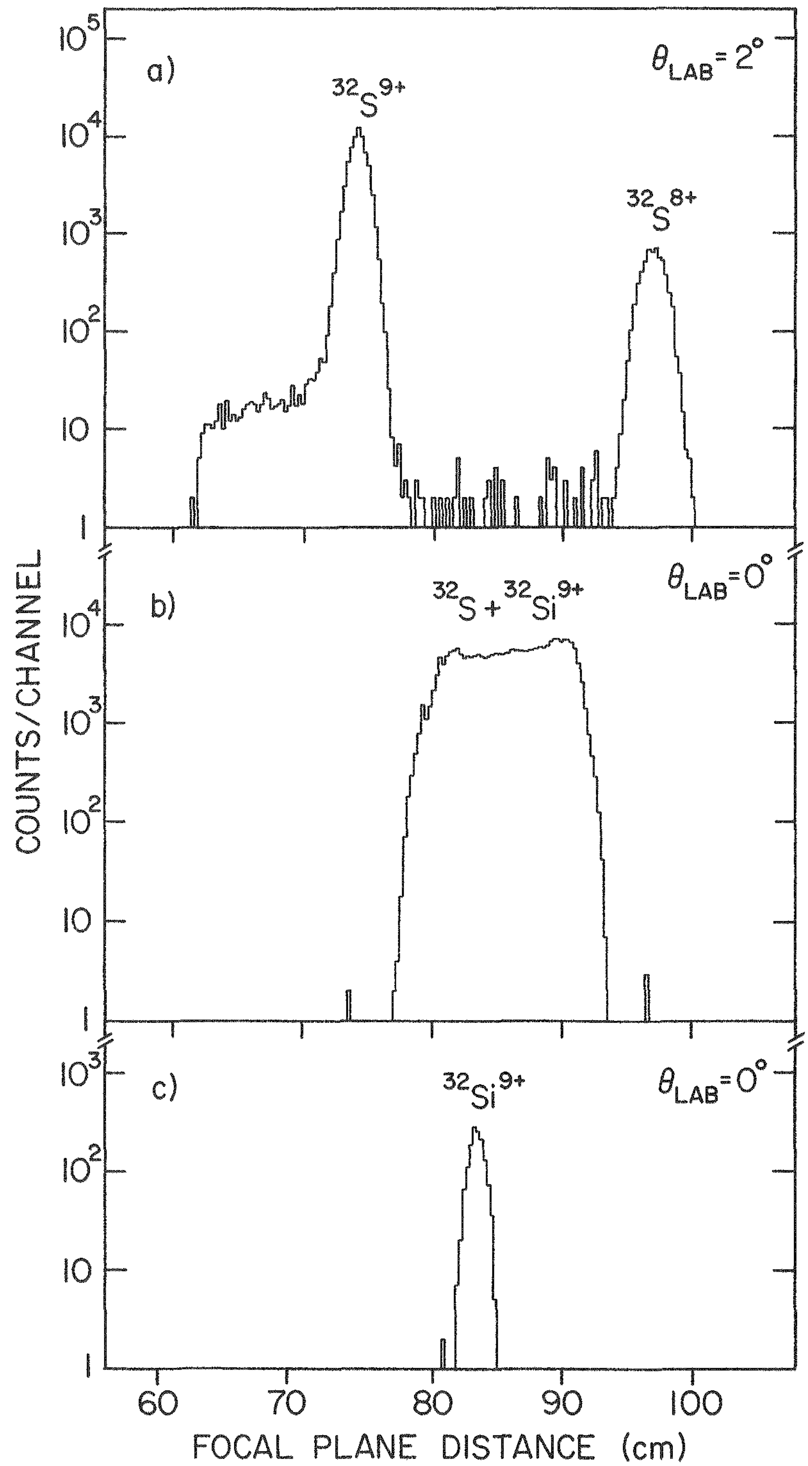

Fig. III-10. Position spectra measured in the focal plane detector of the split-pole spectrograph for 80-MeV ^{32}S and ^{32}Si ions incident on a 1.5 mg/cm^2 thick Al foil stack in the spectrograph target chamber (see Fig. III-9). (a) Full spectrum at θ_{lab} = 2°; (b) partially blocked spectrum at 0°; and (c) fraction of the ions from spectrum (b) gated by ΔE and E_{total} signals (see Fig. III-11) corresponding to $^{32}Si^{9+}$.

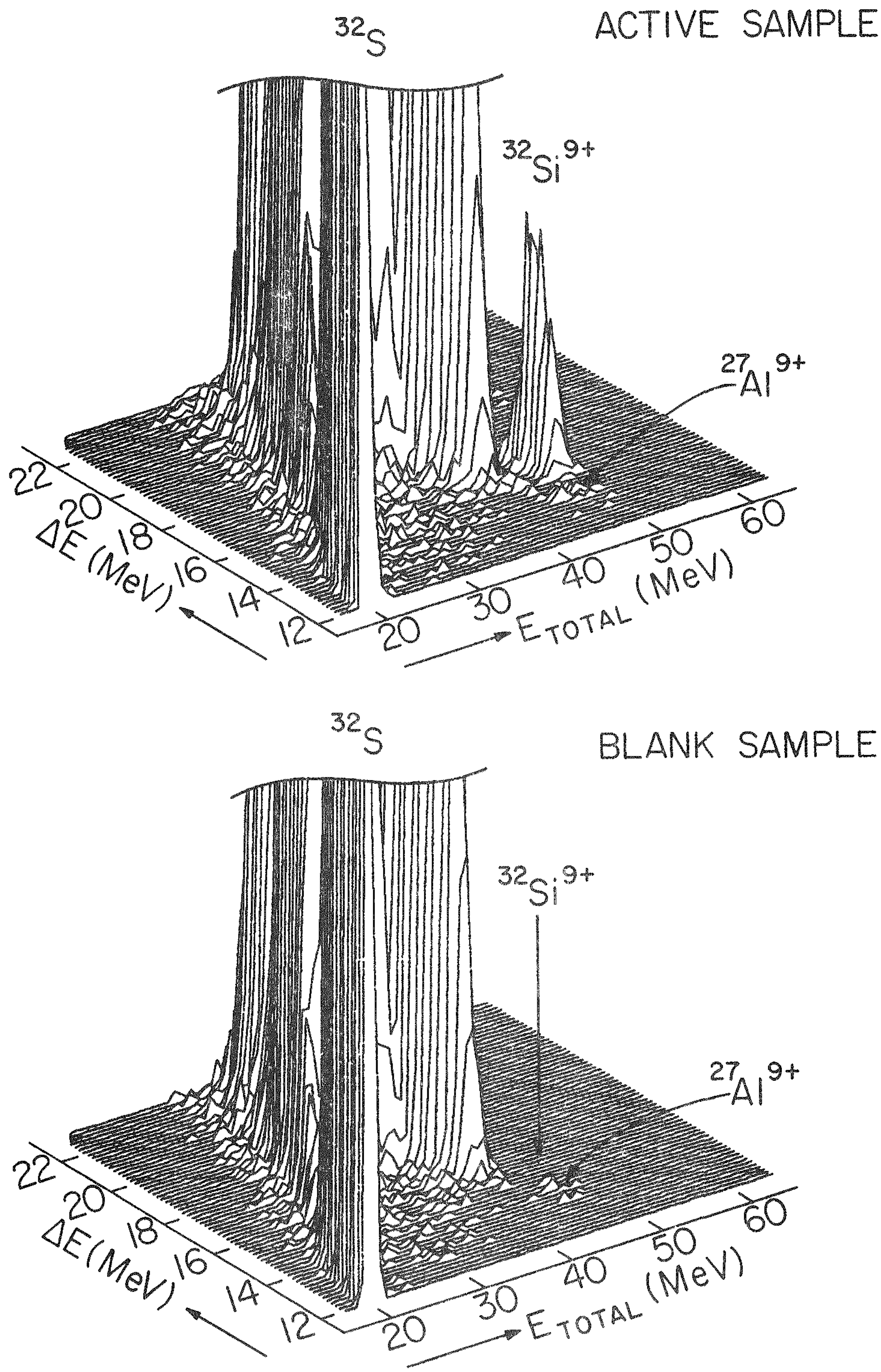

Fig. III-11. Specific energy loss ΔE vs total energy signals E_{total} in the focal plane detector for ions from an active K_2SiF_6 sample (700 $^{32}Si^{9+}$ counts in 20 min) and an inactive K_2SiF_6 sample (zero $^{32}Si^{9+}$ counts in 11 min, $^{32}Si/Si \leq 1 \times 10^{-10}$).

$^{26}Al/^{27}Al$ ratios in the range of 10^{-10} to 10^{-11} have been measured from irradiated and chemically processed ^{26}Mg samples yielding the following cross sections as a function of center-of-mass energies: 7.5 ± 2.4 mb (5.0 ± 0.1 MeV), 37.3 ± 6.3 (5.5 ± 0.1), 28.2 ± 4.5 (6.0 ± 0.1), 42.6 ± 6.9 (6.4 ± 0.1), 65.2 ± 9.4 (6.7 ± 0.1). Figure III-12 illustrates the clear separation of ^{26}Al ions from background peaks of ^{26}Mg and ^{27}Al ions in the spectrograph focal plane detector. The measured cross sections support recent calculations[2] of stellar reaction rates of the $^{26}Mg(p,n)^{26g}Al$ reaction, where theoretical cross-section values were used.

[2] J. D. King, Astrophys. J. 230, 558 (1979).

c. Use of the Linac for Radioisotope Detection

W. Henning, W. Kutschera, R. K. Smither, and J. L. Yntema

In the technique of high-sensitivity isotope detection with heavy-ion accelerators, one makes use among other things of the energy-loss dependence of high-energy ions on the nuclear charge Z. Since the energy-loss difference between Z's increases with energy (see Fig. III-13), it is suggestive to use the linac for such measurements. The major difficulty that arises is the phase stability between injected beam pulses and the linac acceleration field, which is normally assured by a phase-lock system which senses the actual beam arrival time. In the present measurements, we attempted to accelerate and identify ions of the radioisotope ^{32}Si studied previously at the tandem, with only a few picoamperes background beam from the omnipresent ^{32}S isobar. We found that the adjusted phase-lock system ran stably on currents of 10 pA $^{32}S^{14+}$.

The ^{32}Si ions were separated from ^{32}S through an energy range measurement at a beam energy of 230 MeV. In Fig. III-13, we plot the normalized yield for events detected in a ΔE-E Si surface barrier detector telescope (5 μ, 100 μ) at 0° behind a gold absorber of variable thickness. The yield is normalized to the ^{32}S background beam. An excess of ions is transmitted through the thickest Au absorber when the beam originates from a sample in the tandem sputter source that contains ^{32}Si. The ΔE signals for these events are consistent with those expected for ^{32}Si.

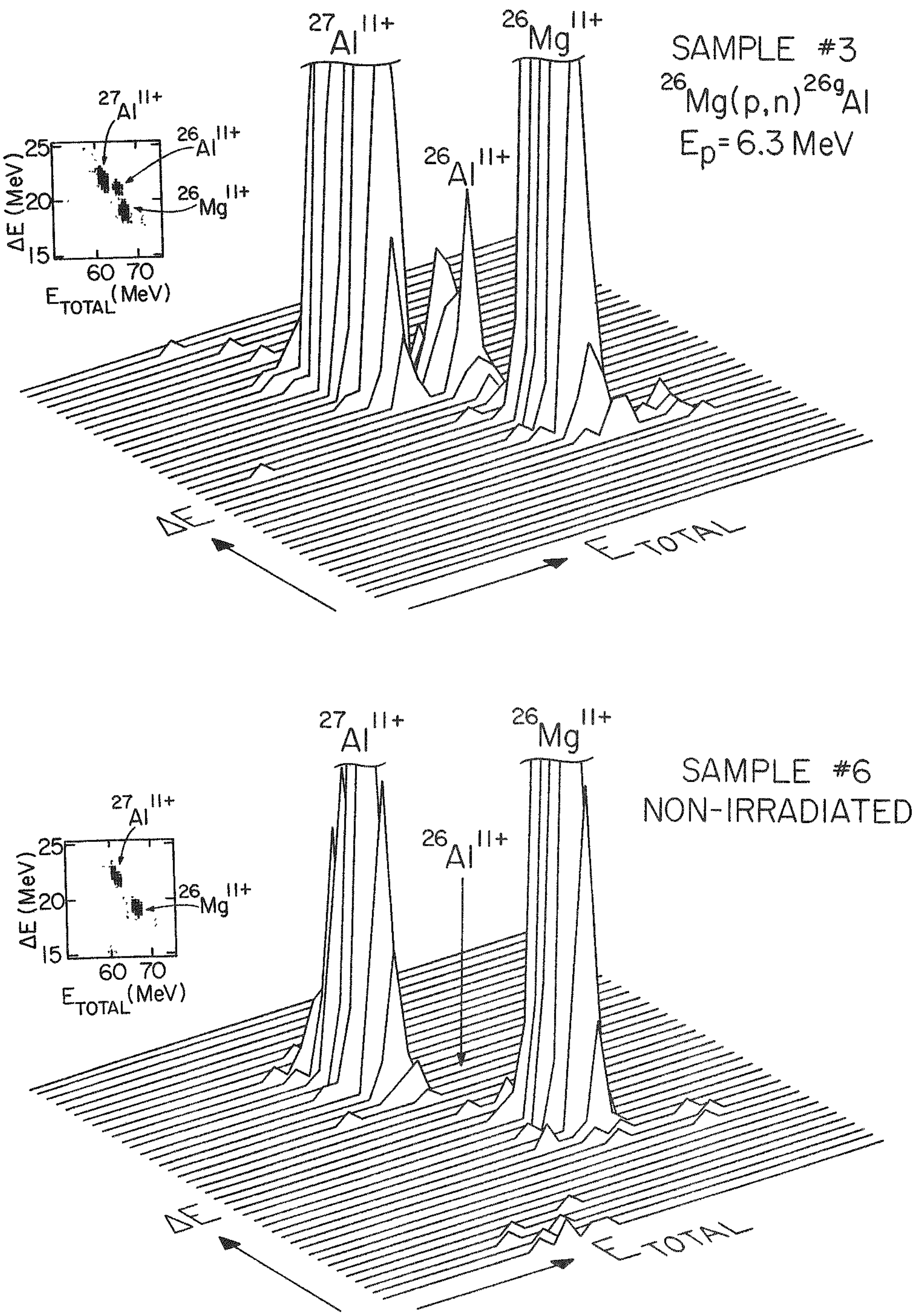

Fig. III-12. Two-dimensional spectra of the total energy E_{total} vs differential energy loss ΔE measured in the split-pole magnetic spectrograph. Sample #3 shows a clearly separated $^{26}Al^{11+}$ peak, whereas zero $^{26}Al^{11+}$ counts are observed for the nonirradiated sample #6. The inserts to the left are projections onto the E_{total} vs ΔE plane. The vertical scale of the contour plots is linear and the same for both samples. The ^{27}Al and ^{26}Mg background peaks of sample #3 are about 10 times stronger than the ^{26}Al peak.

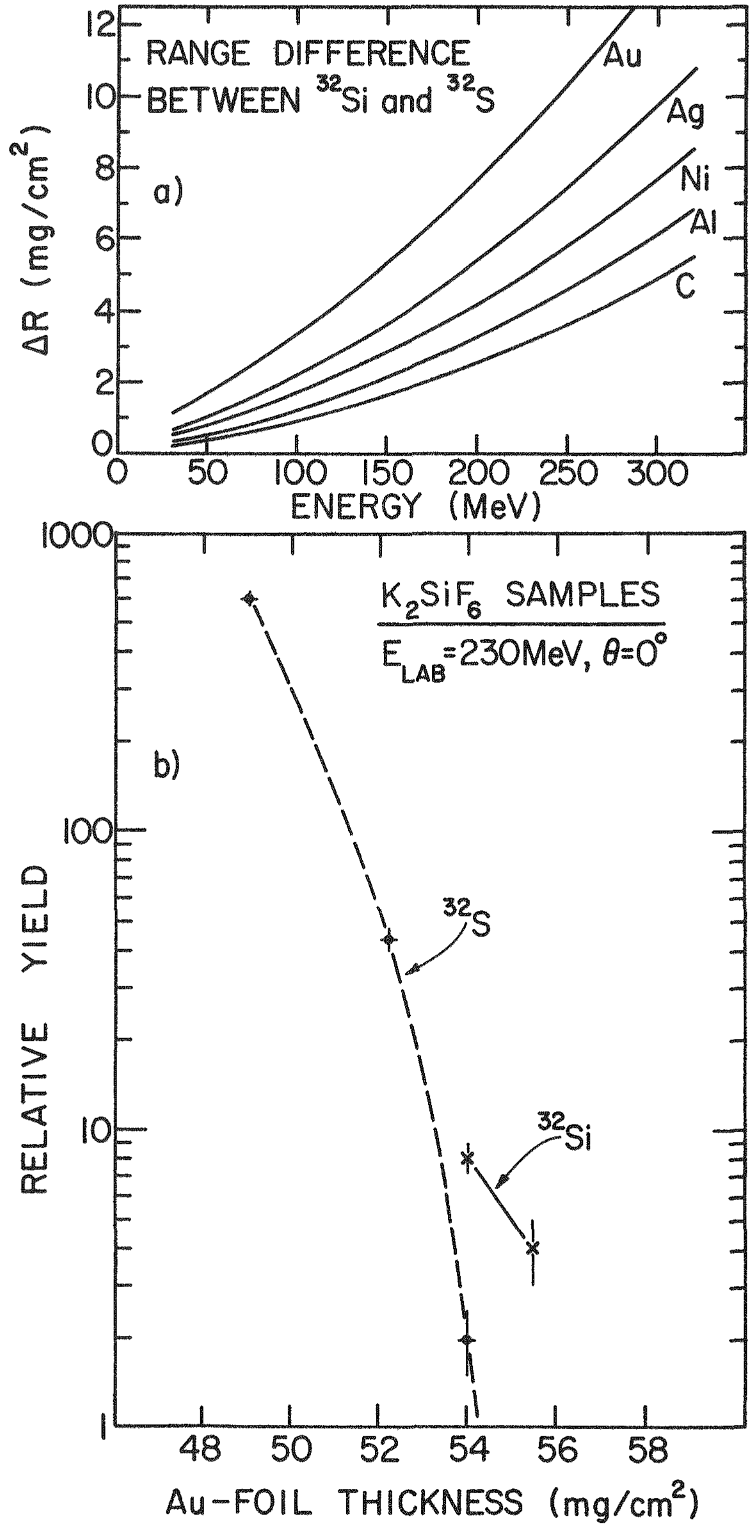

Fig. III-13. (a) Range difference between ^{32}Si and ^{32}S ions in different absorber materials. (b) Ion yield measured in the telescope for a sample with no ^{32}Si (dashed curve) and a sample containing ^{32}Si with a $^{32}Si/Si$ ratio of approximately 10^{-8}.

IV. NEUTRON AND PHOTONUCLEAR PHYSICS

INTRODUCTION

The Argonne neutron-physics program has traditionally included measurements of the fundamental properties of the neutron. An experiment to measure the electric dipole moment of the neutron using stored ultracold neutrons has been undertaken. It is hoped that a sensitivity of around 1×10^{-25} e-cm will be attained by the end of 1981. This will provide a test of the Weinberg-Salam standard model in the gauge theory of weak interactions.

The photoneutron research program at Argonne is centered around studies of non-E1 giant resonances in nuclei, basic reaction mechanisms in light nuclei and fundamental properties of the deuteron. The importance of the photoneutron method lies in its ability to reach regions of excitation in nuclei which are inaccessible by other traditional neutron-induced reactions. Much of the effort during this year was devoted to the completion and testing of a new multidirectional electron beam transport system. This new system not only permits more accurate spin assignments of resonances, but also enables an accurate measurement of the relative angular distribution for the photodisintegration of the deuteron. Some of our effort has also involved the study of the systematic errors one encounters when performing such accurate angular distribution measurements. In addition, we have completed an exhaustive search for the M1 giant resonance in ^{208}Pb below 8.4 MeV. This study employed the extended neutron flight paths.

Another area of the photonuclear program involves photon scattering from medium- and heavy-weight nuclei. Observations of inelastic photon scattering from vibrational nuclei provide information about the coupling between two collective modes of nuclear excitation. These studies are performed in collaboration with the University of Illinois. This research makes use of the photon monochromator associated with the MUSL-II electron microtron at the University of Illinois and high-resolution NaI(Tl) spectrometers which were developed at Argonne. During the year we have observed elastic and inelastic photon scattering from a broad range of nuclei. These results should provide a stringent test of the dynamic collective model.

A. NEUTRON RESEARCH

a. Measurement of the Electric Dipole Moment of the Neutron

V. E. Krohn, G. R. Ringo, J. M. Carpenter,* T. O. Brun,* T. W. Dombeck,† J. W. Lynn,† and S. A. Werner‡

The object of this new project is to measure the electric dipole moment (EDM) of the neutron using stored ultracold neutrons (UCN). The EDM of the neutron, because it can be measured with such great sensitivity, has provided a useful challenge to fundamental particle theories. It has been instrumental in disposing of about 15 of these and at the moment is on the edge of testing the very successful Weinberg-Salam gauge theory of the weak interaction. In the currently popular model, which gives CP nonconservation, the EDM is calculated as 1.6×10^{-24} e-cm [S. Weinberg, Phys. Rev. Lett. 37, 657 (1976)]. The present measurements give an upper limit at that value.

The sensitivity of the measurement to the length of time neutrons spend in the measuring apparatus makes the use of UCN stored in containers an attractive possibility for this measurement. These neutrons have velocities lower than 7 m/s and are totally reflected at all angles by the container walls. They can be stored for 100 seconds or more. By using a shutter on the container, opened only when the source is on, a pulsed source of UCN can give as large a number of stored neutrons as a steady state source with a flux equal to the peak flux of the pulsed source. Argonne has such a source in the IPNS project (ZING-P') and UCN have been produced at that facility by reflection of 400 m/s neutrons from a package of synthetic mica crystals on a 230 m/s rotor synchronized to the pulses from the source.[1] Figure IV-1 shows one velocity component of the reflected neutrons. About 70% of the neutrons below 7 m/s in the figure are UCN. The measured flux of UCN suggests that when the pulsed source now under construction (IPNS-1) becomes available, it will give a contained density of UCN that

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†University of Maryland, College Park, Maryland.

‡University of Missouri, Columbia, Missouri.

[1] T. O. Brun, J. M. Carpenter, V. E. Krohn, G. R. Ringo, J. W. Cronin, T. W. Dombeck, J. W. Lynn, and S. A. Werner, Phys. Lett. 75A, 223 (1980).

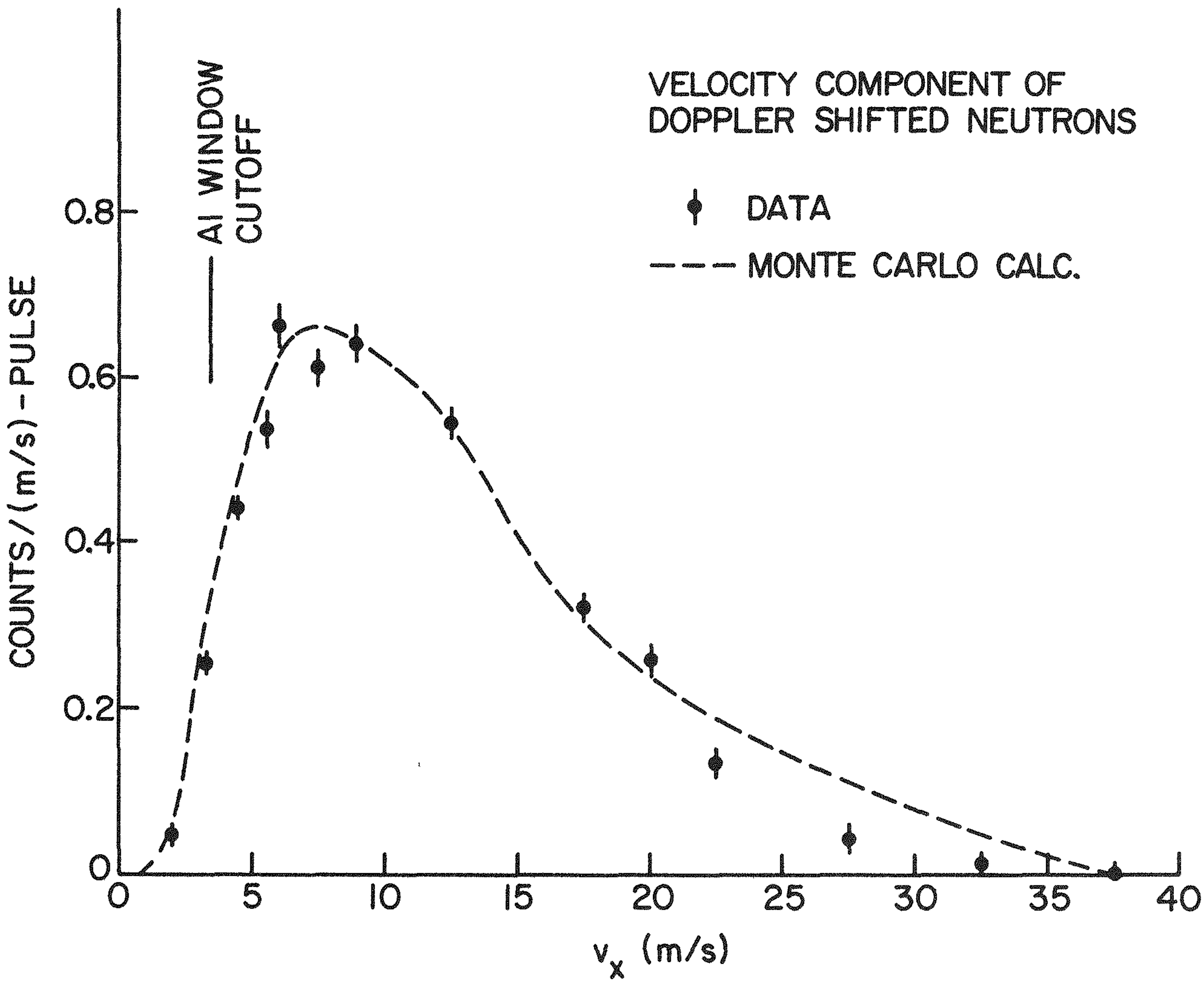

Fig. IV-1. The reflected neutron spectrum for the velocity component toward a counter placed at the end of a guide tube 30 cm from the crystal is shown. The velocities were determined by time of flight. The counter had an aluminum window which reflected neutrons below 3.2 m/s. The dashed curve is a Monte Carlo calculation which took into account the counter efficiency and the experimental arrangement.

will be competitive with the high-flux reactor at Grenoble where another EDM measurement is planned.

The UCN will be stored in a container which will be located in a combined magnetic and electric field and the precession rate will be measured with the electric field parallel and antiparallel to the magnetic. If a density of more than 3 UCN/cc can be achieved, and this appears quite possible, the accuracy of the EDM measurement will be improved from the present 1.6×10^{-24} e-cm to about 1×10^{-25} e-cm. In all probability, this will require the further suppression of some significant sources of systematic errors below the levels that were tolerable in the present measurements (e.g., leakage currents from the electric field plates).

This experiment involves a sizable collaboration with university scientists.

b. Energy Levels in ^{155}Sm

R. K. Smither, K. Schreckenbach,* H. G. Börner,* W. F. Davidson,* T. von Egidy,* D. D. Warner,* R. F. Casten,† M. L. Stelts,† and A. I. Namenson‡

Additional average resonance neutron capture (ARC) experiments were performed on the ^{154}Sm($\bar{n}$,γ)^{155}Sm reaction with the filtered beam facility at the Brookhaven HFBR reactor using neutron beams with energies of 2 keV and 24 keV. These new ARC data were combined with data taken earlier at Argonne and at Grenoble on both ARC and thermal neutron capture experiments on the high-energy primary transitions and conversion electron and crystal diffraction data on the low-energy portion of the (n,$\bar{e}$) and (n,γ) spectra, to extend the level scheme of ^{155}Sm up to 2-MeV excitation. The level scheme (see Fig. IV-2) is interpreted in terms of the Nilsson model with some Coriolis mixing and ΔN=2 coupling. Five negative parity and six positive parity bands have been identified and the model explains the level scheme of ^{155}Sm quite well. It is hoped that our understanding of the ^{155}Sm level scheme will suggest an approach to the analysis of the level schemes of ^{153}Sm and ^{151}Sm, and possibly ^{149}Sm. The level scheme undergoes dramatic changes in this region suggesting rather large changes in the nuclear structure.

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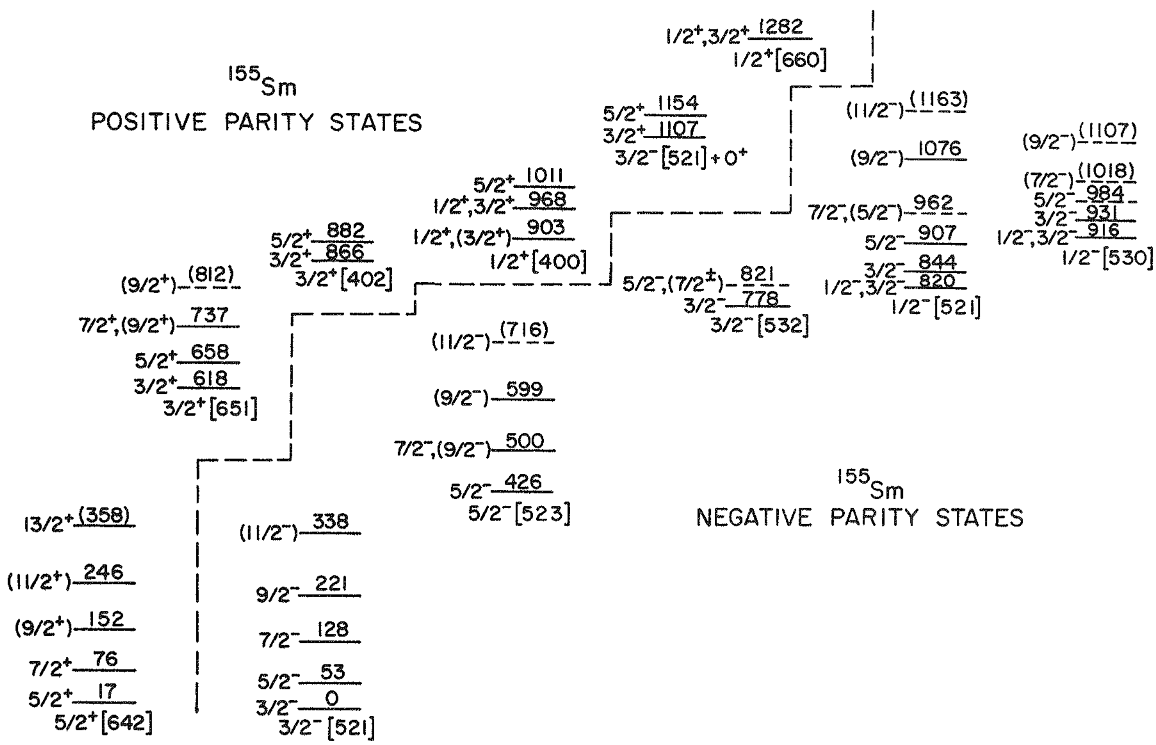

Fig. IV-2. Levels identified in ^{155}Sm. Level energies are given in keV. Nilsson assignments are in square brackets.

B. PHOTONUCLEAR PHYSICS

a. Photon Scattering by the Giant Dipole Resonance in Medium Weight Nuclei

T. J. Bowles, R. J. Holt, H. E. Jackson, R. M. Laszewski,* R. D. McKeown, A. M. Nathan,* J. R. Specht, and R. Starr*

Photon scattering is one of the most unambiguous and revealing reactions for the study of the properties of the giant dipole resonance (GDR). The intensity of the inelastic scattering provides a sensitive measure of the extent to which the GDR is coupled to other degrees of freedom such as collective surface and rotational excitations. We have studied the elastic and inelastic photon scattering for a series of targets ranging from ^{40}Ar to ^{96}Mo, in an experiment in which the incident photon energy is measured and the elastic and inelastic scattering are resolved. The energy of the incident photon was determined with a resolution of 100—200 keV by using the tagged bremsstrahlung beam generated at the University of Illinois MUSL-II superconducting microtron. Scattered photons were observed in a large volume NaI(Tl) spectrometer with an energy resolution ∿500 keV over the photon range 15—22 MeV. Figure IV-3 shows the differential cross sections measured at 120° for elastic and inelastic scattering to the first excited state in ^{60}Ni. Within statistics the inelastic scattering is described by a constant branching ratio of 0.15 relative to the elastic component. In order to avoid the complication in interpretation of this quantity posed by the interference of Thomson scattering with the elastic resonance scattering, we have analyzed our data by fitting it to the scattering cross section for a GDR consisting of two Lorentzians. The solid curves of Fig. IV-3 are best fits to the data. The resonance parameters obtained from the fit to the elastic scattering are in fair agreement with values reported in the literature. The inelastic scattering is fit by branching ratios, $\Gamma_{\gamma 1}/\Gamma_{\gamma 0}$, of 0.3 and 0.15 for the upper and lower energy Lorentzians, respectively. Similar data have been obtained for ^{52}Cr, ^{56}Fe, ^{92}Mo, and ^{96}Mo. The dynamic collective model is currently being applied to those nuclei.

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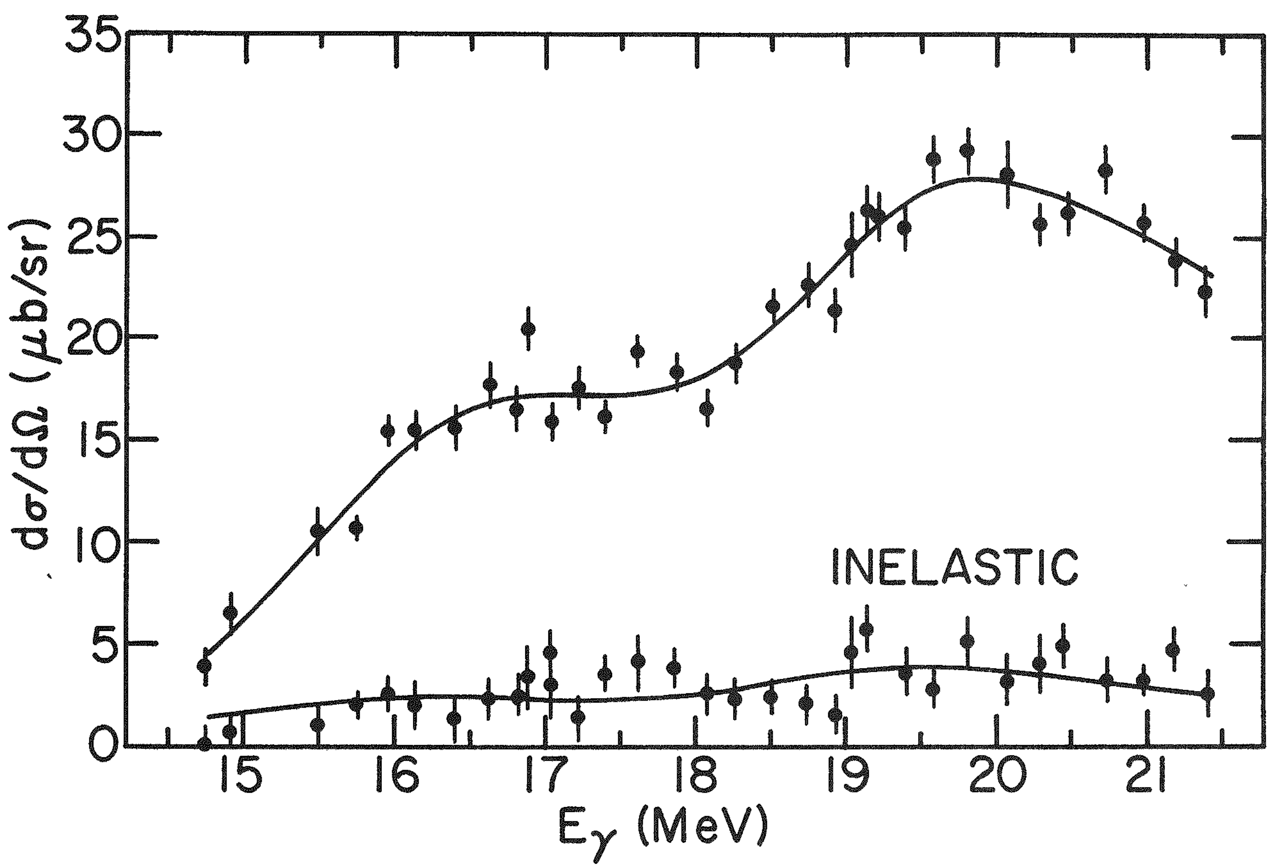

Fig. IV-3. Elastic and inelastic photon scattering results for ^{60}Ni. The curves represent a two-Lorentzian fit to the data.

b. Photodisintegration of the Deuteron

R. J. Holt, H. E. Jackson, R. D. McKeown, J. R. Specht, and K. E. Stephenson

The deuteron is the simplest nuclear system for the study of the meson exchange and virtual isobar effects. Theoretical predictions indicate that the angular distribution of photoneutrons near threshold should be sensitive to final state interactions and momentum dependent effects in the N-N potential. Furthermore, the measurements[1] at Mainz of the D(γ,p) reaction at 0° were in disagreement with all theoretical predictions at moderate photon energies. Thus, it is essential to have accurate measurements of the angular distribution of photoneutrons from the D(γ,n) reaction from threshold to 20 MeV.

(i) Angular Distributions

Plans are underway to make relative angular distribution measurements at 45°, 90°, 135°, and 155° from threshold to $E_\gamma \sim 20$ MeV. These measurements will exploit the newly constructed multidirectional electron beam transport system. In addition, elements for the 155° beam line are under construction. In order to ensure that the desired accuracy ($\lesssim$3%) is achieved, a number of preliminary experiments have been carried out to study the magnitude of systematic errors. In particular, the problem of multiple neutron scattering in the target was studied in great detail. Measurements of the angular distributions are expected to be performed later this year.

(ii) The D($\gamma,\vec{n}$)H Reaction

Theoretical studies indicate that this reaction is particularly sensitive to meson-exchange effects in the N-N potential. Previous measurements of this kind typically have been of relatively low statistical accuracy, and thus, have not provided a conclusive test of the theoretical predictions. With the intense-pulsed bremsstrahlung source available at the ANL high-current electron linac and with the development of high-efficiency neutron polarimeters, we plan to measure the photoneutron polarization from this reaction with high accuracy. Design of the polarimeters is underway. These measurements are expected to proceed after the angular distributions have been studied.

[1] R. J. Hughes, A, Zieger, H. Wäffler, and B. Ziegler, Nucl. Phys. A267, 329 (1976).

c. Photoneutron Studies of E1, M1, and E2 Excitations in ^{13}C

R. J. Holt, R. M. Laszewski, H. E. Jackson, J. E. Monahan, and J. R. Specht

Photoneutron spectra for the $^{13}C(\gamma,n_0)^{12}C$ reaction were observed over the energy region 6.5 to 9.3 MeV at angles of 90° and 135°. The photoneutron measurements were analyzed in terms of a multilevel R-matrix formalism. The $^{12}C(n,n)^{12}C$ reaction channel was explicitly included in this analysis. The effects of potential capture were directly observed in the photoneutron spectra. The ground-state radiative widths $\Gamma_{\gamma 0}$ for resonances in this energy region were deduced from the R-matrix interpretation of the results. In Table IV-I the deduced $\Gamma_{\gamma 0}$ are compared with the theoretical predictions of Barker,[1] Jäger *et al.*,[2] Kissener *et al.*,[3] and Kurath.[4] The weak-coupling model of Barker is in good agreement with the results of the experiment for the E1 excitations at 7.69 and 8.19 MeV. Weak coupling models have been successful in describing the neutron widths of those resonances. However, it is surprising that the more detailed calculations of Jäger *et al.* and Kissener *et al.* are in disagreement with the present results.

TABLE IV-I. Comparison of the ground-state radiative widths with theoretical predictions.

E_γ (MeV)	$M\mathcal{L}$	$\Gamma_{\gamma 0}$ (eV) Present experiment	Barker	Jäger *et al.*	Kissener *et al.*	Kurath
7.56	E2	0.11 ± 0.015	. . .	. . .	. . .	0.18
7.69	E1	0.6 ± 0.1	0.71	0.60	1.54 }	3.78[a]
8.19	E1	7.0 ± 0.9	5.49	0.53	0.89 }	
8.89	M1	5.4 ± 0.5	. . .	. . .	6.13	13.87—14.78

[a]Only the integrated strength from both E1 excitations is quoted.

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[1]F. C. Barker, Nucl. Phys. 28, 96 (1961).

[2]H. U. Jäger, H. R. Kissener, and R. A. Eramzhian, Nucl. Phys. A171, 16 (1971).

[3]H. R. Kissener, A. Asward, R. A. Eramzhian, and H. U. Jäger, Nucl. Phys. A219, 601 (1974).

[4]S. Cohen and D. Kurath, Nucl. Phys. 73, 1 (1956); D. Kurath, private communication.

d. Doorway Resonances in ^{29}Si

R. J. Holt, H. E. Jackson, and J. R. Specht

Since the discovery of doorway states in ^{29}Si, the theoretical advances in describing the ^{28}Si+n system have become more sophisticated. In the most recent theory the $^{28}Si(n,\gamma)^{29}Si$ reaction was described within the formalism of Boridy and Mahaux by constructing particle-vibration basis states. These theories indicate that there may be a substantial amount of radiative strength for doorway resonances above the present experimental observations.

New (γ,n) work will be performed which makes use of the 25-m neutron flight paths and the newly installed multidirectional electron transport system. A $^{29}SiO_2$ quartz sample is currently being fabricated for this work.

e. Isospin Splitting of the Giant Dipole Resonance in ^{60}Ni

T. J. Bowles, R. J. Holt, H. E. Jackson, R. D. McKeown, A. M. Nathan,* and J. R. Specht

The question of isospin splitting of the giant dipole resonance in non-self-conjugate nuclei has long been an issue in photonuclear physics. Although there are a number of theoretical calculations which predict the amount of splitting and the relative strength of the two components $T_<$ and $T_>$, the experimental information is very sketchy.

The photoneutron reaction is a selective probe for isospin splitting. For example, in a (γ,n_0) reaction only photoneutrons from the $T_<$ component are allowed by the isospin selection rules; whereas in (p,γ) reactions both components can be excited.

In the present work we have observed the cross section at 90° for the $^{60}Ni(\gamma,n_0)^{59}Ni$ reaction for the first time. The 25-m flight paths and high current pico-pulse made it possible to achieve sufficient energy resolution to identify ground-state photoneutron transitions. The first results indicate only one broad peak in the (γ,n_0) cross section which is consistent with isospin splitting of the giant dipole resonance.

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*University of Illinois, Urbana, Illinois.

f. High-Resolution Photoneutron Study of E1 and M1 Transitions in ^{208}Pb

R. J. Holt, H. E. Jackson, R. M. Laszewski, and J. R. Specht

The photoneutron cross section of ^{208}Pb was observed using a very high resolution time-of-flight spectrometer. The cross sections were observed in the photoneutron energy range 16 to 1000 keV and at reaction angles of 90° and 135°. The deduced ground-state radiative widths were calibrated to the well-known $^{2}H(\gamma,n)^{1}H$ reaction cross section. The 7.99-MeV resonance, previously believed to be an M1 excitation, is shown to be an E1 resonance. Current progress in the search for the collective M1 resonance in ^{208}Pb and recent theoretical predictions of the properties of the giant M1 resonance are reviewed. Finally, the present high-resolution observations[1] in conjunction with previous photoneutron polarization measurements were employed in order to deduce the s-d wave admixtures for eight E1 excitations.

[1] R. J. Holt, H. E. Jackson, R. M. Laszewski, and J. R. Specht, Phys. Rev. C 20, 93 (1979).

g. Scattering-Matrix Elements for Nuclear Reactions Involving Photons

J. E. Monahan, R. J. Holt, and R. M. Laszewski

The transformation of scattering-matrix elements from a representation appropriate for particle channels to one that describes photon channels is rederived.[1] Previous derivations have ignored an ambiguity in the relative phase of the vector potential for magnetic and electric multipole radiation. The resultant ambiguity in the S-matrix transformation seems to be a source of confusion about the relative phases of the various terms that contribute to the polarization of particles produced in photonuclear reactions.

[1] J. E. Monahan, R. J. Holt, and R. M. Laszewski, Phys. Rev. C 20, 389 (1979).

h. R-Matrix Analysis of the ^{6}Li+n System Below 4 MeV

R. J. Holt, P. T. Guenther,* A. B. Smith,* and J. F. Whalen*

This work was performed in collaboration with the Applied Physics Division. The neutron total and differential cross sections were measured

*Applied Physics Division, ANL.

below 4 MeV using the ANL fast neutron generator. This is the first systematic measurement of the differential cross section for the $^{6}Li(n,n)^{6}Li$ reaction in the MeV region. The absence of definite resonances above 500 keV and the relatively large number of open reaction channels renders the Li+n system difficult to interpret in terms of a multichannel R-matrix theory. Nevertheless, efforts are in progress to understand the reaction mechanisms for this system.

i. Neutron Interactions with Carbon-12 in the Few-MeV Region

A. B. Smith,* R. J. Holt, and J. F. Whalen*

This work[1] was performed in collaboration with the Applied Physics Division. Neutron total cross sections of natural carbon are deduced from the observed transmission of approximately monoenergetic neutrons through carbon samples of various thicknesses. The measurements extend from ∿0.1 to 4.5 MeV, with resolutions of ∿2 to 100 keV. Neutron differential elastic scattering cross sections of natural carbon are measured from 1.5 to 4.0 MeV at incident neutron energy intervals of ≲100 keV, over an angular range of ∿20 to 160 deg and with energy resolutions of 20 to 50 keV. The experimental results are interpreted in terms of a multilevel R-function analysis. Results are compared with measured and evaluated neutron total and scattering cross sections and with scattered neutron polarization data reported in the literature. The present work[1] suggests that the observed neutron total and scattering cross sections of carbon are physically consistent and suitable for use as a reference standard in experimental studies of neutron processes. The R-function interpretation provides a convenient description of neutron total and scattering cross sections of carbon as a function of both angle and energy.

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*Applied Physics Division, ANL.

[1] A. Smith, R. Holt, and J. Whalen, Nucl. Sci. Eng. 70, 281 (1979).

V. THEORETICAL PHYSICS

INTRODUCTION

The nuclear theory program deals with the properties of nuclei and with the reactions and interactions between nuclei and a variety of projectiles. Our main areas of concentration are the following.

A. Heavy-ion direct reactions at nonrelativistic energies.

B. Nuclear shell theory and nuclear structure.

C. Nuclear matter and nuclear forces.

D. Intermediate-energy physics and pion-nucleus interactions.

E. High-energy collisions of heavy ions.

Recent progress and plans for future work in these five main areas of concentration and a summary of other theoretical studies currently in progress or recently completed are presented below.

A. HEAVY-ION DIRECT-REACTION THEORY

In heavy-ion collisions at moderate energies, several states in both the projectile and target may be excited. The excitation amplitudes and the couplings between excited states are usually too strong to be properly accounted for by DWBA calculations. Coupled-channels calculations for such systems are quite difficult because of the large number of coupled equations that results from the partial-wave decomposition of a few channels. For example, a system consisting of two 0^+ nuclei, one with an excited 2^+ state and the other with 2^+, 3^-, and 5^- states results in 76 coupled equations for each value of the total angular momentum. In addition, for collisions involving nuclei such as Ca and a rare earth, with a bombarding energy of several hundred MeV, the wavelength will be 0.5 fm or less, so that small stepsizes are necessary. Coulomb coupling is important at distances of up to several hundred Fermi.

Such inelastic scattering processes do, however, offer the possibility of probing nuclear structure. Both Coulomb and nuclear excitation are important, and the interference between them can be sensitive to the details of the nuclear structure models assumed in the analysis. Second-order transitions are important in the mutual excitation of both the projectile and target; the required matrix elements are also dependent on the nuclear models used. Thus it is desirable to be able to carry out detailed, accurate quantum-mechanical calculations for heavy-ion inelastic scattering in which low-lying states in both the projectile and target are populated.

At Argonne we have developed a program that will allow us to do such calculations. We are now beginning to apply the program to the analysis of inelastic scattering data.

a. Heavy-Ion Coupled-Channels Calculations—Computational Techniques

M. H. Macfarlane, S. C. Pieper, and M. J. Rhoades-Brown

As was described in last year's report, sequential iteration with Padé approximants is an efficient method for heavy-ion coupled-channels calculations. We have compared this method with a variety of alternative iterative techniques—the method of moments, the Born series (also with Padé approximants), and Austern's variant of Sasakawa iteration. We conclude that Padé-accelerated sequential iteration is the most rapidly convergent method for heavy-ion calculations and we will use it in our coupled-channels extension of Ptolemy. Papers describing this study and the computation of coupled-channels Coulomb wavefunctions have been published.[1]

[1] M. Rhoades-Brown, M. H. Macfarlane, and Steven C. Pieper, Phys. Rev. C 21, 2417 and 2436 (1980).

The computer program Ptolemy makes use of the smooth angular-momentum dependence of DWBA scattering amplitudes by computing these amplitudes at widely-spaced values of L and using interpolation. Heavy-ion coupled-channels amplitudes have a very similar dependence on angular momentum and we have extended the techniques previously developed to the coupled-channels calculations. The method used for DWBA inelastic amplitudes can be applied directly to the coupled-channels inelastic amplitudes; however, the extrapolation of the coupled-channels elastic amplitude requires a method that accounts for the removal of flux from the elastic channel. We have developed such a method and tested it in a variety of calculations. By using these methods, it is possible to obtain cross sections with 1% accuracy for reactions to which thousands of partial waves contribute, with the explicit computation of amplitudes for only a few dozen partial waves.

b. Ptolemy; A Computer Program for Heavy-Ion Direct Reactions. Coupled-Channels Extension

M. H. Macfarlane, S. C. Pieper, and M. J. Rhoades-Brown

We have started writing the necessary extension of Ptolemy to allow coupled-channels calculations of heavy-ion inelastic scattering. The three techniques described in Sec. a will all be included. The program has been designed to permit the use of a variety of models (rotational, vibrational, microscopic) for the channel-coupling form factors. For the moment we are concentrating on first- and second-order rotational coupling. As in earlier development of Ptolemy, much effort has been put into developing an input format that is flexible and easy to use.

c. Ptolemy; A Computer Program for Heavy-Ion Direct Reactions. Light-Ion Extension

R. P. Goddard,* M. H. Macfarlane, and S. C. Pieper

Work begun in the previous year on a light-ion extension of Ptolemy has been completed. The program Ptolemy can now evaluate spin observables in elastic scattering and in transfer reactions using finite-range DWBA. Arbitrary spin-dependent and tensor optical potentials may be used in elastic and transfer calculations.

*University of Wisconsin, Madison, Wisconsin.

B. NUCLEAR SHELL THEORY AND NUCLEAR STRUCTURE

The best available nuclear wave functions, in particular those of the many-particle shell model, have been used to illuminate various aspects of nuclear levels, transitions and interactions. We have placed particular stress on the properties of light nuclei ($A \lesssim 50$) and on the interactions of intermediate-energy pions with such nuclei.

a. Parity-Changing Excitations of Light Nuclei in (π,π') Scattering

T.-S. H. Lee and D. Kurath

Calculations of inelastic pion-nucleus cross sections with the distorted wave impulse approximation have been extended to treat excitation of states having parity opposite to that of the ground state, a subject of much current experimental interest. The input nuclear transition density is obtained from shell-model calculations wherein opposite-parity states are treated in a space obtained by promoting a single nucleon to the next oscillator level in all possible ways. Treatment of several nuclei in the upper 1p shell indicates that distinctive angular distributions are obtained which are determined by the orbital (L) and spin (S) values of the transition density. Furthermore marked differences between π^+ and π^- scattering are produced by the sensitivity of pions to whether the excitations are predominantly of neutron or proton nature. A striking example is the excitation of a $9/2^+$ state in ^{13}C in which the predicted cross sections favor π^- scattering by a factor of 9 over π^+ scattering, in agreement with recent experimental results. (See Fig. V-1.) Calculations for ^{13}C have been completed, and nearby nuclei such as ^{14}N will be studied to look for unusual features due to nuclear structure which should be evident in recently-measured data.

b. Nuclear Effect of Parity-Violating Interaction

W. D. Teeters* and D. Kurath

In connection with a pending experiment to measure the effect of the parity violating term from weak interactions in ^{10}B, we have calculated the expected size of the mixing term for the relevant states. These are J=2 states differing in isospin as well as parity. We have made shell-model calculations to test the stability of the wave functions to the

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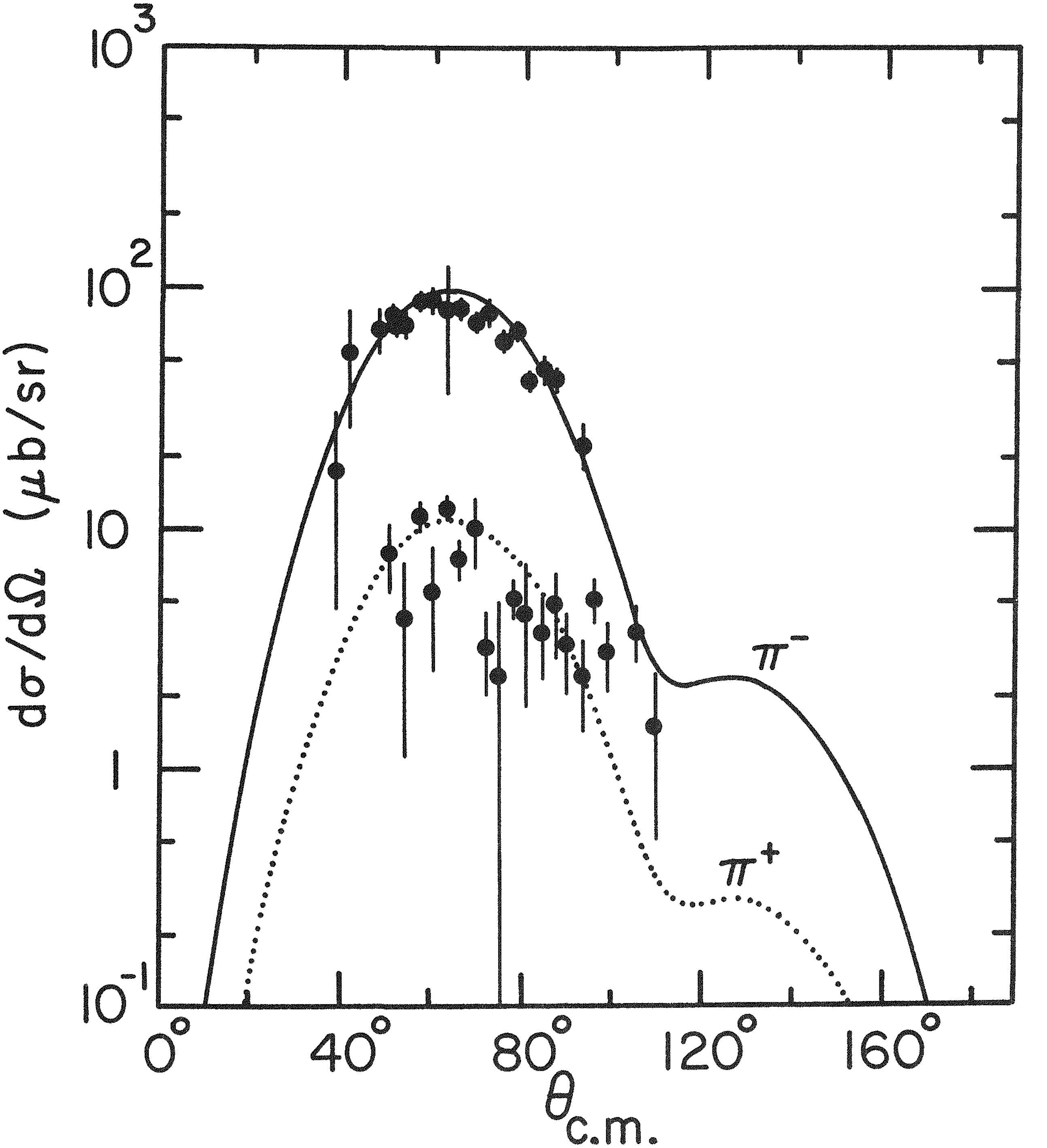

Fig. V-1. Cross sections calculated for excitation of the $J=9/2^+$ state at 9.50 MeV in ^{13}C by 162-MeV π^- (solid line) or π^+ (dotted line) beams. Data points are supplied by S. J. Tripp (private communication).

nuclear model, and estimated the parity-mixing matrix-element for a one-body approximation of the parity-violating interaction. The size of matrix element obtained is encouraging for the prospects of the experiment. However, we plan to calculate the effect using a two-body approximation for the parity-violating interaction, which should give a more reliable result.

c. Workshop in Nuclear Structure Physics

D. Kurath

A summer workshop on theoretical nuclear structure was held at Gull Lake, Michigan from August 27 to September 7, 1979. About 55 graduate students and postdoctoral researchers attended. Six major lecturers included the co-organizers, G. Bertsch of Michigan State University and D. Kurath of Argonne. Lecture notes were published by Springer-Verlag.

d. 8^- States in ^{54}Fe

R. D. Lawson, T.-S. H. Lee, and W. D. Teeters*

Recent electron-scattering measurements indicate that four T=1 8^- states ranging in energy from 8.3 MeV to 10.7 MeV and one T=2 8^- state (at ∿13.3 MeV) are strongly excited in ^{54}Fe and carry most of the M8 sum rule strength. A shell-model calculation has been carried out in which it is assumed that the ground state of ^{54}Fe is described by $(f_{7/2})^{14}_{I=0,T=1}$ and the 8^- states by $[g_{9/2,1/2} \times (f_{7/2})^{13}_{JT}]_{I=8^-,T_f}$. If one takes the $(f_{7/2})^2$ interaction energies from ^{54}Co and the $(g_{9/2}f_{7/2})$ matrix elements from the True-Schiffer central potential, the calculated spectra and their M8 strengths are in qualitative agreement with experiment. Furthermore, in the absence of any $(g_{9/2}f_{7/2})$ interaction the configuration $[g_{9/2,1/2} \times (f_{7/2})^{13}_{7/2\ T=\frac{1}{2}}]_{8,1}$ (which corresponds to pure neutron excitation) will lie about 4.5 MeV below $[g_{9/2,1/2} \times (f_{7/2})^{13}_{7/2\ T=\frac{3}{2}}]_{8,1}$. Consequently the yrast 8^- state is expected to be mainly the former configuration and hence to be mainly neutron excitation. Thus it would be expected to show up approximately nine times more strongly in π^- scattering than in π^+. When the shell-model wave functions are used, the predicted ratio $R_\pi = \sigma(\pi^-)/\sigma(\pi^+) \approx 34$ at $\theta \approx 80°$ and the $\sigma(\pi^-)$ scattering has a magnitude of $\approx$0.06 mb/sr.

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It is also found that the calculated ratio R_π for the higher 8^- states are distinctively different from each other. Thus because of the strong isospin dependence of the pion-nucleon interaction, measurements of R_π and the absolute cross section will give important nuclear structure information.

e. The Microscopic Structure and Group Theory of the Interacting Boson Model

Harry J. Lipkin

Possible composite models for the bosons in the IBM are investigated, using groups smaller than SU(6) which have six dimensional representations. The two candidates are SU(3) and SU(4) which describe composite models made from pairs of spin-one bosons and spin-3/2 fermions, respectively. The SU(4) model is the fermion pair model proposed by Ginocchio, who obtains sets of states in one-to-one correspondence with the states of the SU(6) IBM classification even though there is no SU(6) group in the SU(4) model. This correspondence is investigated in detail, and it is shown that the states in the Ginocchio model filling a fermion major shell with n_k states include all states analogous to those in the IBM for n bosons with $n \leq n_k$. The states for $n > n_k$ in the fermion model are then determined by particle-hole symmetry. The concept of seniority plays a crucial role in this analysis; three kinds of seniority numbers can be defined which are related to Casimir operators of groups appearing in the chains used to classify the states. The three seniorities can be defined in both models, but only two of them are described by the same group in both models. The third seniority is described by different groups, SU(5) in the boson model and quasispin Sp(2) in the fermion model, but the seniority numbers defined in both cases have the same values and the same physical meaning.

f. Reaction $^{15}N(t,p)^{17}N$

H. T. Fortune,* G. E. Moore,* L. Bland,* M. E. Cobern,* S. Mordechai,* R. Middleton,* and R. D. Lawson

Properties of the low-lying states of ^{17}N observed in the $^{15}N(t,p)^{17}N$ reaction have been studied. Below 4.5 MeV seven states have been observed with strengths that would be expected when two (sd)-shell neutrons are added to ^{15}N. The energies of these negative parity states have been calculated using the $\{(\pi p_{1/2})^{-1}\ (\nu d_{5/2}, \nu s_{1/2}, \nu d_{3/2})^2\}$ model space (with at

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*University of Pennsylvania, Philadelphia, Pennsylvania.

most one neutron in $d_{3/2}$) and the theoretical predictions are in qualitative agreement with the positions of observed states. In addition, states of ^{17}N known to have positive parity are also weakly populated in this reaction. It is shown that some of the observed excitation energies can be understood on the basis of the three-particle $[(sd)^3]$, two-hole $[(p_{1/2})^{-2}]$ weak coupling model.

C. NUCLEAR MATTER AND NUCLEAR FORCES

The microscopic theory of nuclei as systems of interacting nucleons rests on our ability to determine adequate nucleon-nucleon potentials. Homogeneous nuclear matter is an important testing ground because the theory is mathematically well defined and its consequences are sensitive to features of the potentials that do not affect the observable properties of two-nucleon systems. For any density, the energy per particle can be calculated exactly from the amplitude S_2 for the excitation of two particles out of the Fermi sea, which must be obtained from the many-body Schrödinger equation (coupled cluster equations) in a reliable approximation. The Bethe-Goldstone equation yields the lowest order Brueckner approximation for S_2. The Brueckner-Bethe scheme ("hole-line expansion") is designed to produce systematic corrections. The validity of the approximation depends on features of the potential and must be established by numerical tests. These tests include various internal consistency checks and comparison with variational calculations. The lowest-order Brueckner approximation is always inadequate even for purposes of a rough orientation. So far all tests indicate that inclusion of the three-hole-line corrections gives a reasonable approximation. At present we can calculate the two-hole-line term accurately, the three-hole-line term with about 10% accuracy, and the four-hole-line term within a factor of 2. The saturation point for an assumed two-body potential can be located within an uncertainty of order 0.1 fm^{-1} in Fermi momentum and 2 MeV in binding energy. More accurate calculations are desirable, but the present accuracy is good enough to obtain physically interesting results.

During this year we have applied the Brueckner-Bethe hole-line expansion to the full Reid potential. This is the first time that an adequate nuclear-matter calculation has been done for a two-body potential that fits the scattering data. We have further checked the validity of the hole-line expansion by comparing its results with those of a different but equally plausible truncation of the coupled-cluster equations. Also, the variational method has been further developed by applying the Fermi-hypernetted-chain method to the electron fluid.

During the coming year we plan to make calculations for more potentials that fit the scattering data, e.g., the Paris and Bonn potentials. If, as expected, no potential can account for the saturation properties of nuclear matter, we will modify the calculations to include virtual delta particles in the two- and three-body terms. We also expect to further test the validity of the method by doing calculations with different choices of single-particle spectra.

The calculations of three-hole-line corrections to S_2 are, at present, quite time consuming. In view of the inadequacy of the Bethe-Goldstone equation, it is important to invent a simple equation for S_2 that includes the main effects of the three-hole-line corrections. We are now in a position to pursue this goal since we can calculate the quantities to be approximated.

a. Nuclear-Matter Calculation Using the Reid Potential

B. D. Day

The Reid potential gives a good account of nucleon-nucleon scattering and deuteron properties, and it is important to know what it predicts for the saturation point of nuclear matter. The published Reid potential is defined only in two-body partial waves with $J \leq 2$, but individual higher partial waves can give substantial contributions to the binding energy of nuclear matter. In these partial waves we used unpublished potentials of Reid that are consistent with empirically-determined phase shifts and reduce to the one-pion-exchange potential at long range. The resulting potential was used in a detailed nuclear-matter calculation including two-, three-, and four-hole-line terms. Because of cancellation among different partial waves, the contribution to the binding energy per nucleon from the potential in higher partial waves was only about 1 MeV. The saturation point occurred at $k_F = 1.52 \pm 0.1$ fm^{-1} and -17.0 ± 2 MeV (the empirical saturation point is at 1.36 ± 0.08 fm^{-1} and -16 ± 1 MeV). Zabolitzky's calculations of light nuclei and earlier less accurate nuclear-matter calculations lead us to suspect that the correct empirical saturation point will not be obtained for any realistic two-body potential. If this expectation is confirmed by further calculations, we must conclude either that three-body forces are required in any model of the nucleus as a system of point nucleons or that other degrees of freedom must be included.

b. Numerical Comparison Between the Hole-Line Expansion and the Coupled-Cluster Equations

B. D. Day and J. G. Zabolitzky

The Brueckner-Bethe hole-line expansion is equivalent to a certain truncation of the coupled-cluster equations: The nth order calculation [denoted BB(n)] includes all diagrams with 2, 3, . . . n hole lines. All tests so far confirm the validity of this method. The Bochum truncation of the coupled-cluster equations is based on the same intuitive ideas but implies a different grouping of diagrams. The n-body calculation in this scheme [denoted CC(n)] includes all n-hole-line diagrams, but in addition certain classes of diagrams are summed to infinite order in the number of hole lines. At present we do not know which of these two schemes is more accurate. Therefore, if the two schemes were to give substantially different numerical results, this would imply substantial uncertainty in present nuclear-matter calculations. Using the results of the BB(4) calculations that were carried out earlier for the v_6 (Reid) potential, we have estimated the results of CC(n) calculations for n = 2, 3, 4. In each order the BB(n) and CC(n) results differ by less than the expected uncertainty in either. This result is reassuring and gives additional evidence for the validity of the Brueckner-Bethe method. A paper describing this work is being prepared.

c. Hypernetted-Chain Euler-Lagrange Equations and the Electron Fluid

J. G. Zabolitzky

The Fermi hypernetted-chain approximation for variational calculations has previously been applied to nuclear and neutron matter and to liquid ^3He, systems in which short-range correlations are dominant. It is therefore of great interest to apply it to the electron liquid, which is a benchmark system for any method purporting to treat long-range correlations properly. This has been done, using the suggestion of Lado that the modulus squared of the Fermi-gas Slater determinant be approximated by an appropriate Jastrow product of two-body functions. This is a tremendous simplification because it reduces the Fermi hypernetted-chain equations to the same form as those for bosons.

The resulting Euler-Lagrange variational equations have been solved to obtain least upper bounds to the ground-state energy over a large range of density and spin polarization. The resulting approximate distribution and structure functions satisfy certain exact relationships in the high- and low-density limits, as well as in the long wavelength limit at any density. The calculated energies are in excellent agreement with both coupled-cluster perturbational and Monte-Carlo calculations. Hence this version of the Fermi-hypernetted chain method gives an excellent description of the electron liquid. The method also properly treats both short- and long-range correlations simultaneously, which has long been an unsolved problem in the Fermi-hypernetted-chain method. A paper describing this work has been submitted to Physical Review B.

d. Nucleon-Nucleon "Potentials" and Two-Body Hamiltonians

F. Coester

The physical significance of nucleon-nucleon "potentials" depends on their relation to the two-nucleon mass operator. These relations are examined for phenomenological potentials. Momentum-space Bethe-Salpeter amplitudes with one particle on the mass shell approximate "half-off-shell" T matrices defined in the framework of the Haag-Ruelle theory. This implies a relation between "potentials" derived from a Bethe-Salpeter equation and effective two-body mass operators. An invited paper was presented at the "Topical Meeting on the Meson Theory of Nuclear Forces and Nuclear Matter," Bad Honnef, West Germany, June 12-14, 1979.[1]

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[1] The Meson Theory of Nuclear Forces and Nuclear Matter (Proceedings of the Conference, Bad Honnef, Germany, 12-14 June 1979), ed. by D. Schütte, K. Holinde, and K. Bleuler (Bibliographisches Institut, Zurich, 1980), p. 155.

D. INTERMEDIATE ENERGY PHYSICS

Traditional nuclear theory assumes that nuclei can be treated as a collection of nucleons with the effects of other degrees of freedom absorbed in the phenomenological Hamiltonian. Pion-nucleus reactions are expected to probe the nuclear structure so described. Thus a desirable theoretical framework is a straightforward extension of conventional nuclear theory to include pions. The interactions should then allow pion production and absorption without modifying the single nucleon states. We have shown for the NNπ system that such models can be fully relativistic. Substantial simplifications result when the baryons move with nonrelativistic velocities.

We have studied inelastic pion-nucleus scattering with a hybrid model. The transition matrix elements of the effective π-nucleus potential are calculated in the impulse approximation using off-energy shell π-nucleon scattering amplitudes and shell-model wave functions. The diagonal matrix element of the effective potential is determined empirically by fitting to elastic scattering data. This model has proved quite useful in the interpretation of inelastic scattering data.

a. Canonical Scattering Theory for Relativistic Particles

F. Coester

A multichannel relativistic scattering theory can be formulated in a manner similar to the nonrelativistic multichannel theory. The problems of existence and completeness of wave operators are formally the same. Poincaré invariance and cluster separability of the S operator impose non-trivial restrictions. The solutions were reviewed in an invited talk at the "Conference on Mathematical Methods and Applications of Scattering Theory," 21-25 May 1979 at Catholic University. The proceedings were published.[1]

[1] Mathematical Methods and Applications of Scattering Theory (Proceedings of a Conference, Washington, D.C., 21-25 May 1979), ed. by J. A. DeSanto, A. W. Sáenz, and W. W. Zachary (Springer-Verlag, Berlin-Heidelberg-New York, 1980), p. 190.

b. Phenomenological Relativistic Quantum Mechanics of the NNπ System[1]

M. Betz and F. Coester

We have provided the theoretical basis for a class of models with the following features. The elementary degrees of freedom are the nucleon N, the isobar Δ, and the pion π. The elementary nucleon and pion are also physical.

[1] Phys. Rev. C 21, 2505 (1980).

The Δ is unstable. The interactions are introduced in the invariant mass operators. The basic ingredients are (1) a πN interaction $v_{N\pi}$ which is a vertex $\pi N \rightleftarrows \Delta$ in the resonant (3,3) partial wave and a direct two-body interaction in the other partial waves, (2) a nucleon-nucleon interaction v_{NN} acting in the 3-body $NN\pi$ partial wave designed to fit nucleon-nucleon scattering below the pion threshold, and (3) a two-body interaction V_0 in the NN and $N\Delta$ channels which has transition matrix elements $NN \rightleftarrows N\Delta$.

c. Construction of an $NN\pi$ Model

M. Betz and T.-S. H. Lee

We have constructed a concrete model of the type described above (Sec. V.Db) by the following procedure. In order to simplify the calculations all two-body interactions are parameterized in each partial wave by a low-rank separable kernel. The parameters in $v_{N\pi}$ and v_{NN} are first determined to fit scattering data for $E_\pi \lesssim 300$ MeV and $E_N \lesssim 300$ MeV. The parameters of V_0 were then determined by fitting to NN phase shifts for energies up to 800 MeV. Good fits to Arndt's phase shifts have been obtained for all partial waves with $\ell \leq 4$. With all parameters so determined, we have calculated cross sections for πd elastic scattering and for the reaction $\pi d \rightarrow pp$. The results agree well with the available data in the energy region near the resonance. The results are quite sensitive to a proper treatment of the interactions in the three-body channels. Preliminary results for πd polarization cross sections are encouraging. We plan to test and refine this model by further study of pion production in proton-proton collisions and πd polarization cross sections.

d. A DWIA Model for Microscopic Analyses of Pion-Nucleus Inelastic Scattering

T.-S. H. Lee

Recent studies of pion-nucleus reactions have indicated that the excitation of nuclear states by pions can be adequately described in the impulse approximation. In this simple picture, pions can be used to probe the relative strengths of neutron and proton excitations. This is attributed to the fact that the $\pi^+p(\pi^-n)$ interaction is 9 times stronger than the $\pi^+n(\pi^-p)$ interaction. Based on the impulse approximation, we have developed a DWIA program to relate the structure of nuclear excited states to (π,π') cross sections. Since true pion-absorption by nuclei is not well understood, our present analyses rely on phenomenological optical potentials which are determined by fitting the elastic scattering cross sections. However, the excitations of nuclear states by pions are expressed microscopically in terms of the known elementary πN interactions and nuclear transition form factors. The model has been tested extensively in the region where the nuclear transition form factors are known accurately, and has been found to be valid in the energy region near the (3,3) resonance. The model has then been used to explore in great detail the structure of several 1p-shell nuclei, ^{18}O and many heavier nuclei. These results will be described separately in the Secs. V.De and V.Df. We plan to improve the model to also describe the (π,π') scattering at energies beyond the resonance region.

e. Inelastic Pion Scattering from ^{18}O

T.-S. H. Lee and R. D. Lawson

The inelastic scattering of 164-MeV pions from ^{18}O is studied using the distorted wave impulse approximation in momentum space. The sensitivity of the predictions to various shell-model descriptions of the yrast 2^+ state is examined in detail. The excitation of the triplet of states $(4_1^+, 0_2^+, 2_2^+)$ near 3.7 MeV and the $(3_1^-, 0_3^+, 2_3^+)$ triplet at about 5.2 MeV are also investigated within the context of the shell model. In order to explain the scattering to natural parity states [those with angular momentum J and parity $(-1)^J$], one must enhance the theoretical results by about the same factor as needed to explain the $B(EJ;\, 0 \rightarrow J)$ transition rates obtained from electromagnetic excitation. The results of these calculations, together with similar ones for 1p-shell nuclei, show that the DWIA can provide an adequate explanation of the experimental data provided one uses "realistic" shell-model form factors (i.e., ones that fit other nuclear data). Thus inelastic pion scattering in this energy regime, analyzed in terms of the DWIA, can be used to extract nuclear structure information.

f. Studies of Pion-Nucleus Double-Charge-Exchange (π^+,π^-) Reactions

S. Chakravarti,* T.-S. H. Lee, Guang-Lie Li,† and Chu-Hsia Li†

The characteristic feature of the pion-nucleus double-charge-exchange (DCE) reaction is that at least two nucleons are involved in the underlying reaction mechanism. The DCE reaction is therefore expected to be very useful for studying two-nucleon correlations inside nuclei. In the impulse approximation, the DCE mechanism is made up of two elementary πn single-charge-exchange scatterings mediated by intermediate states Φ_n of the nucleus with (Z+1) protons and (N-1) neutrons. We are studying the DCE reactions based on two different models. In the first model, it is assumed that the momentum transfer in each single-charge-exchange process is small and hence only very few low-lying intermediate states Φ_n contribute to the DCE mechanism. This model has been cast into a coupled-channel calculation by Chakravarti. Calculations for the DCE reaction $^9Be(\pi^+,\pi^-)^9C$(g.s.) have been completed using the wave functions of Cohen and Kurath. It is found that the calculated cross sections are sensitive to the detailed structure of the intermediate states. Compared with the available tentative data, the calculated differential cross sections agree reasonably well in magnitude but not in shape. A paper describing this study is being prepared by Chakravarti and Lee. The second model assumes that the momentum transfer in each single-charge-exchange process can be very large and hence all intermediate states contribute to the DCE mechanism. By using the closure approximation to sum the intermediate nuclear states, the model relates the DCE cross sections to the two-body transition densities between the initial and final nuclear states. Calculations are also being done for the target nucleus ^{9}Be. Our main focus now is to determine the validity of these two models in various energy regions where the experimental data are available.

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E. MICROSCOPIC CALCULATIONS OF HIGH-ENERGY COLLISIONS OF HEAVY IONS

The study of heavy-ion collisions at energies greater than about 100 MeV/nucleon seems the only way of obtaining information about the properties of nuclear matter at high densities and temperatures and about possible new states of nuclear matter. Because of the relatively large mean free path and associated large nonequilibrium phenomena, an adequate description of such collisions must in general be a microscopic one. We initiated and are continuing (with A. D. MacKellar) classical equations-of-motion (CEOM) calculations of high-energy heavy-ion (HE-HI) collisions for laboratory energies from about 100 MeV to about 1 GeV/nucleon (Refs. 1—3). The CEOM method is a completely microscopic but classical approach whose essence is the calculation of all nucleon trajectories using a two-body potential between all pairs of nucleons. The unique feature of this approach is that it includes finite-range interaction effects (in particular potential-energy effects) for realistic potentials and hence does not assume that nuclear matter is a dilute fluid as do the Boltzmann-equation/cascade calculations.

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[1] A. R. Bodmer and C. N. Panos, Phys. Rev. C 15, 1342 (1977).

[2] A. R. Bodmer, in Proceedings of the Topical Conference on Heavy-Ion Collisions, Fall Creek Falls State Park, Pikeville, Tennessee, 13-17 June 1977, organized by E. C. Halbert *et al.* (Oak Ridge National Laboratory, 1977), CONF-770602, p. 309.

[3] A. R. Bodmer, in Proceedings of the Symposium on Relativistic Heavy Ion Research, GSI Darmstadt, 7-10 March 1978, edited by R. Bock and R. Stock (Gesellschaft für Schwerionenforschung, Darmstadt, 1978), GSI-P-5-78, Vol. 2, p. 347.

a. Classical-Equations of Motion Calculations of High-Energy Heavy-Ion Collisions

A. R. Bodmer, C. N. Panos,* and A. D. MacKellar†

A paper with the above title has been published.[1] In it we present and discuss results obtained with nonrelativistic CEOM calculations for equal-mass projectile and target nuclei with $A_P = A_T = 20$ (Ne + Ne) at laboratory energies/nucleon of $E_L = 117$, 400 and 800 MeV and at 400 MeV for $A_P = A_T = 40$ (Ca + Ca). A static 2-body potential V_{st} with a reasonable repulsive core and attractive tail is used. V_{st} has been fitted by classical 2-body calculations to $\sigma^{(2)}$—the $\sin^2\theta$ weighted isospin-averaged

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†University of Kentucky, Lexington, Kentucky.

[1] A. R. Bodmer, C. N. Panos, and A. D. MacKellar, Phys. Rev. C22, 1025 (1980).

nucleon-nucleon differential cross section. For $A_P = A_T = 20$ we also use a scattering equivalent momentum-dependent potential V_{tr}. V_{st} and V_{tr} give identical 2-body scattering but are not equivalent for many-body scattering and are used to test for finite-range interaction effects in heavy-ion collisions.

The evolution of central collisions is discussed in detail. For these multiple scattering is large, leading to high momentum components. Dissipation quite generally is larger at lower energies and is appreciable during the final expansion phase of central collisions giving approximately thermalized distributions at the lower E_L. A peak at approximately the same momentum at all angles develops in the momentum distribution near the beginning of the expansion and changes roughly in step with the potential energy; for $A_P = A_T = 20$ at 800 MeV the peak persists to the final distributions. There are appreciable differences in the densities, potential energies and distributions between V_{st} and V_{tr} during the strong interaction stage. However, the final distributions are not significantly different even for $A_P = A_T = 20$ at 800 MeV. For $A_P = A_T = 40$ at 400 MeV a transverse peaking develops in the momentum distribution suggestive of collective effects. Noncentral collisions show typical nonequilibrium features and for larger impact parameters the final distributions show a strong single scattering component. This is true also of the impact parameter averaged distributions which are in fair agreement with experiment.

A partial test of thermal models, made by following selected groups of nucleons, indicates the qualitative validity of these models for central collisions, consistent with the large degree of thermalization found for the momentum distributions. For an impact parameter equal to the nuclear radius only the fireball model is tested and not unexpectedly is found to be inadequate. The outer "spectator" nucleons are only slightly affected, consistent with thermal models; however, there is quite appreciable momentum transfer to the inner "spectator" nucleons.

b. A New Kinetic Equation Description and Extensions of the CEOM Calculations to Include Pauli Blocking Effects

A. R. Bodmer, C. N. Panos,* and A. D. MacKellar†

The results of our CEOM calculations, discussed above, have suggested a plausible description in terms, on the one hand, of "collisions" due to the short-range repulsive core of the 2-body potential and, on the other hand, of potential-energy effects from the average single-particle potential due to the long-range attractive part of the 2-body potential. Corresponding to such a separation of the 2-body potential, one obtains a kinetic equation for which the collision term (of the Enskog type) depends only on the short-range part of the potential and where the long-range part enters through a Vlasov-type one-body term. In particular, this separation can plausibly account for the simultaneous occurrence of multiple scattering together with the distinctive potential-energy effects which we find in our CEOM calculations. This separation has also suggested a way of including Pauli-blocking effects in the CEOM calculations. Changes of momentum violating the exclusion principle are assumed to occur predominantly via the "collisions" due to the repulsive core and can be allowed for as in cascade calculations. The long-range attraction, if adequately representable through an average single-particle potential, would on the average preserve the single-particle phase-space density and hence be compatible with the exclusion principle if the initial density is properly chosen. Although such an approach cannot achieve a fully-consistent synthesis of Pauli and interaction effects, it provides a reasonable way to include the former into the CEOM calculations. Such an extension of these calculations is of importance in providing a reasonable microscopic approach valid down to lower energies (50—200 MeV/nucleon), where there is so far no available microscopic approach.

c. Other Improvements and Extensions of the CEOM Calculations

A. R. Bodmer, C. N. Panos,* and A. D. MacKellar†

More general momentum-dependent potentials, dependent on both the relative radial and angular momentum, are being considered in order to obtain

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better fits to the nucleon-nucleon scattering data and as an aid in obtaining more realistic position distributions for the initial nuclei. The use of auxiliary time-dependent single-particle potentials to obtain improved distributions and reduce the effect of evaporation has been further studied. Some further developments have been made of trajectory and analysis programs for relativistic calculations to $O(v^2/c^2)$.

F. OTHER THEORETICAL PHYSICS

a. Quantum Beats of Recoil-Free Gamma Radiation

J. E. Monahan and G. J. Perlow

The theory of the transmission of frequency-modulated recoil-free gamma rays through a resonant absorber was described in a previous report. The transmitted intensity $I(\omega-\omega',t)$ is derived as a function of laboratory time t and of the difference $(\omega-\omega)$ between the actual frequency of the source and that of the absorber resonance. For fixed values of $\omega-\omega'$, the intensity exhibits interference between different frequency components when considered as a function of t. The harmonic content of this beat phenomenon is sensitive to the value of $\omega-\omega'$ and can be used for the precise measurement of small energy shifts. These results have been published.[1,2]

The intensity $I(\omega-\omega',t)$ is given in terms of an alternating series in power of the thickness of the absorber. This suggests that the higher-order terms in the series may be due to thickness-broadening of the resonant line shapes. If so, it should be possible to use the thin-absorber approximation to I and alter the parameters which describe the line shape to obtain a phenomenological fit in the case of a thick absorber. (This is the approach used in ordinary Mössbauer spectroscopy.) A computer code has been written to test this possibility.

We have also generalized the theory to the case of multiple resonances in the absorber. Very complex interference effects are predicted for the transmitted intensity in this case. It remains to determine whether the quantum-beat method will prove useful in the resolution of closely-spaced lines.

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[1] J. E. Monahan and G. J. Perlow, Phys. Rev. A 20, 1499 (1979).

[2] G. J. Perlow, J. E. Monahan, and W. Potzel, Suppl. J. Phys. (Paris) 41, C1-85 (1980).

b. Angular Distributions in Photoelectron-Photoion Coincidence Spectroscopy

J. E. Monahan and J. H. D. Eland

In photodissociative spectroscopy the anisotropy of the velocity vectors of the dissociated ion fragments are measured. This anisotropy depends on the angle Θ between the transition dipole moment and the direction of emission of the fragment. These simple distributions must be corrected for the effects of rotation (before dissociation) and of finite dissociation velocities to obtain the observed distributions. For fixed wavelength photoelectron-photoion coincidence spectroscopy, where the photoions are detected in coincidence with photoelectrons of known energy, these corrections have not been considered previously. We have derived corrections for rotational effects for initial distributions of the form $\sum a_n \cos^n\Theta$.

c. Nuclear Mass Relations

J. E. Monahan

The derivation of a set of nuclear mass relations $M_j(N,Z)$, $j = 1, 2, \cdots$, based on the condition that the number of n-n, p-p, and n-p interactions must cancel in each relation, has been described in previous reports. It is possible to show that this set exhausts all mass relations of this type in the sense that all such relations give predictions that are linear combinations of those contained in the set. We have also investigated the statistical correlation between these relations and find that the correlation coefficient ρ_{ij} is, for all practical purposes, independent of i and j and is equal to +0.5. Thus, if the estimate of a given nuclear mass M(N,Z) is taken to be the arithmetic mean of the predictions given by K members of the above-mentioned set, the variance of $\overline{M}(N,Z)$ is 0.5 V (1 + 1/K), where V is the variance associated with a single prediction. An invited paper on this subject was presented at the "Sixth International Conference on Atomic Masses," Michigan State University, September 18-21, 1979.[1]

[1] Atomic Masses and Fundamental Constants 6 (Proceedings of the 6th International Conference on Atomic Masses, East Lansing, Michigan, 18-21 September 1979), ed. by J. A. Nolen, Jr. and W. Benenson (Plenum, New York, 1980), p. 151.

VI. THE SUPERCONDUCTING LINAC

R. Benaroya, L. M. Bollinger, R. C. Pardo, K. W. Shepard, J. Aron,*
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INTRODUCTION

The Superconducting Linac Project has two main components, both of which are developmental in nature. One is the specific task of designing, building, and testing a small superconducting linac to serve as an energy booster for heavy ions from the FN tandem electrostatic accelerator. The second, more general part, consists of investigations of various aspects of superconducting rf technology. Although most of these investigations are now aimed at the immediate needs of the booster, many of them are of fairly general interest for accelerator technology.

Both parts of the Superconducting Linac Project are jointly supported and administered by the Chemistry and Physics Divisions.

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*Chemistry Division, ANL.

A. HEAVY-ION ENERGY BOOSTER

The booster project, started in mid-1975, is concerned with the design, construction, installation, and testing of a small superconducting linear accelerator (linac) to serve as an energy booster for heavy-ion beams from the FN tandem accelerator. The principal objectives of the project are to develop a new accelerator technology and to build the prototype for a heavy-ion energy booster that can be used to upgrade the performance of any tandem accelerator. The overall design is highly modular in character in order to provide maximum flexibility for future modifications and/or improvements. Twelve resonators of the planned 24-resonator system were in place in March 1980, and the remaining resonators will be completed and installed during 1980-81.

By the end of the present reporting period, the booster was being used routinely (but not continuously) to provide beams for nuclear-physics research. This operational experience is summarized in Chap. VII of this document.

1. MAIN FEATURES OF THE DESIGN[1]

A schematic representation of the booster as it is expected to be at completion is shown in Fig. VI-1. The heart of the system is the split-ring resonator, a three-gap structure made of superconducting niobium. Superconducting solenoids at frequent intervals confine the radial excursions of the beam. The basic accelerating section of the linac consists of a linear array of these resonators and solenoids within a cryostat that can be isolated from the others both with respect to vacuum and cryogenics.

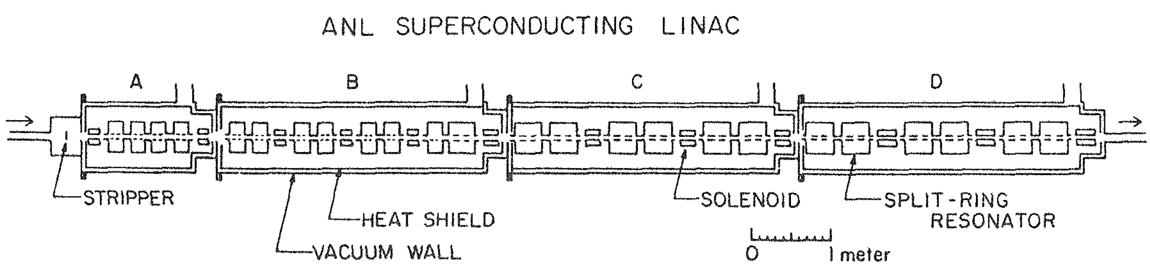

Fig. VI-1. Schematic representation of the planned heavy-ion booster. Sections C and D are installed and in use in March 1980.

[1]For more detail, see the Proposal for ATLAS and its Addendum, obtainable from the Physics Division, Argonne National Laboratory (1978).

The booster makes use of resonators that have two lengths. One type is 35.6 cm long and is optimized for a projectile velocity $\beta \equiv v/c = 0.105$ (sections C and D). A second type is 20.3 cm long and is optimized for $\beta = 0.060$ (sections A and B). The resonators are cooled to a temperature of 4.7°K by forced-flow, two-phase helium from a refrigeration system.

The total rf power required for the booster is only 3.6 kW. This is to be compared with a need for about 2 MW of rf power for an equivalent room-temperature linac. The control of the linac as a whole is accomplished with the assistance of a dedicated small computer. This approach allows rapid tuneup of the accelerator.

For ions in the lower half of the periodic table, the final 4-section booster is expected to provide beam energies that are equivalent to those from a very large (∿30-MV terminal) tandem. A sophisticated beam-bunching system allows the beam out of the linac to have the same good quality as the beam from the tandem. The beam energy can be varied easily by changing the phase and/or amplitude of the last resonator.

2. STATUS OF THE PROJECT

The heavy-ion booster has been a working reality throughout the year ending in March 1980. A total of 12 high-β resonators are installed in sections C and D, and these are used regularly to accelerate beams for the nuclear research program. The layout of the system in March 1980 is shown in Fig. VI-2.

High-β Resonators

Twelve resonators of good quality are installed but, because of a minor failure in a control line, only eleven have been used regularly. The maximum field gradient for individual resonators is typically 4.0 MV/m, when tested in the off-line cryostat, but the useful fields now obtainable in the beam-line cryostats are about 3.0 MV/m, on the average.

Low-β Resonators

A single low-β resonator was temporarily mounted in cryostat C and used for a period of many weeks to accelerate a beam. It operated at a

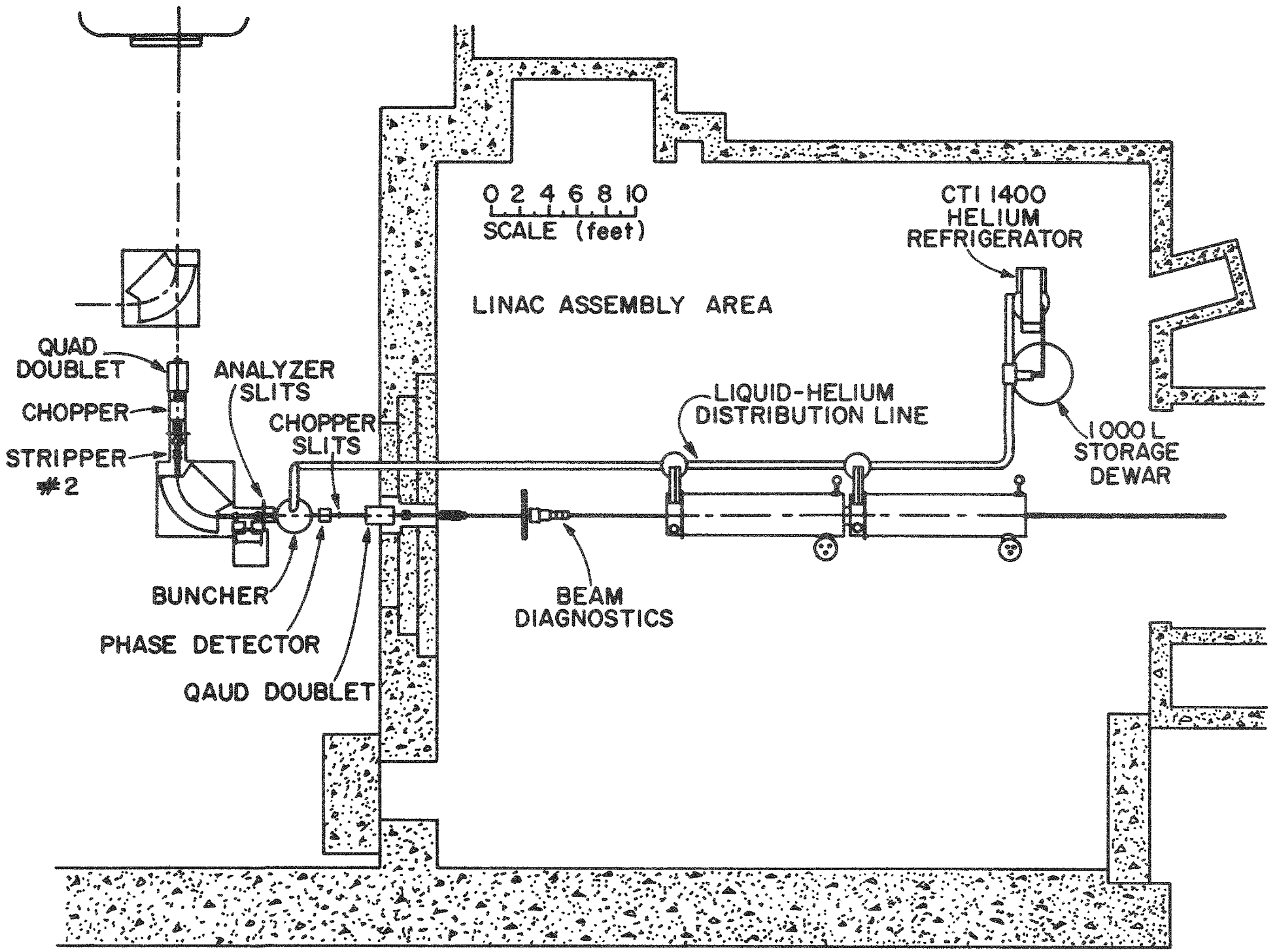

Fig. VI-2. Layout of the booster.

field gradient of 4.0 MV/m during much of this time. Four other low-β resonators are nearing completion.

Cryostats

Cryostats C and D are being used on the beam line. Cryostat A is being modified to accept four low-β resonators. The final unit, cryostat B, is being fabricated in the shop.

Helium Refrigeration and Distribution System

The helium system has been fully functional since mid-1978. However, the present 95-W refrigerator is inadequate for the needs of the complete booster. Consequently, a second refrigerator (a CTI-2800) has been ordered and will be installed in late 1980.

rf Control System

The rf-control system consists of two major parts: a local, hard-wired control unit for each resonator and a computer-based system to monitor and control the system as a whole. The hard-wired circuitry was refined steadily throughout the past year, and no further changes are foreseen.

The computer-based control system is functional but is still being improved. The computer can now set both the amplitudes and phases of resonators, either individually or in response to a users request for a particular beam energy. Several years of additional effort are required before computer control will be refined in all respects.

3. NEAR-TERM PLANS

During the remainder of 1980, the booster will continue to be operated, now with the primary objective of providing useful beams for nuclear-physics experiments. The accelerator will be operated about 40% of the time, with the periods between operation being used to install new components and to improve performance. This projected schedule is summarized by Fig. VI-3.

As may be seen from the figure, a large number of major accelerator improvements are planned for the near future. These include: (a) the

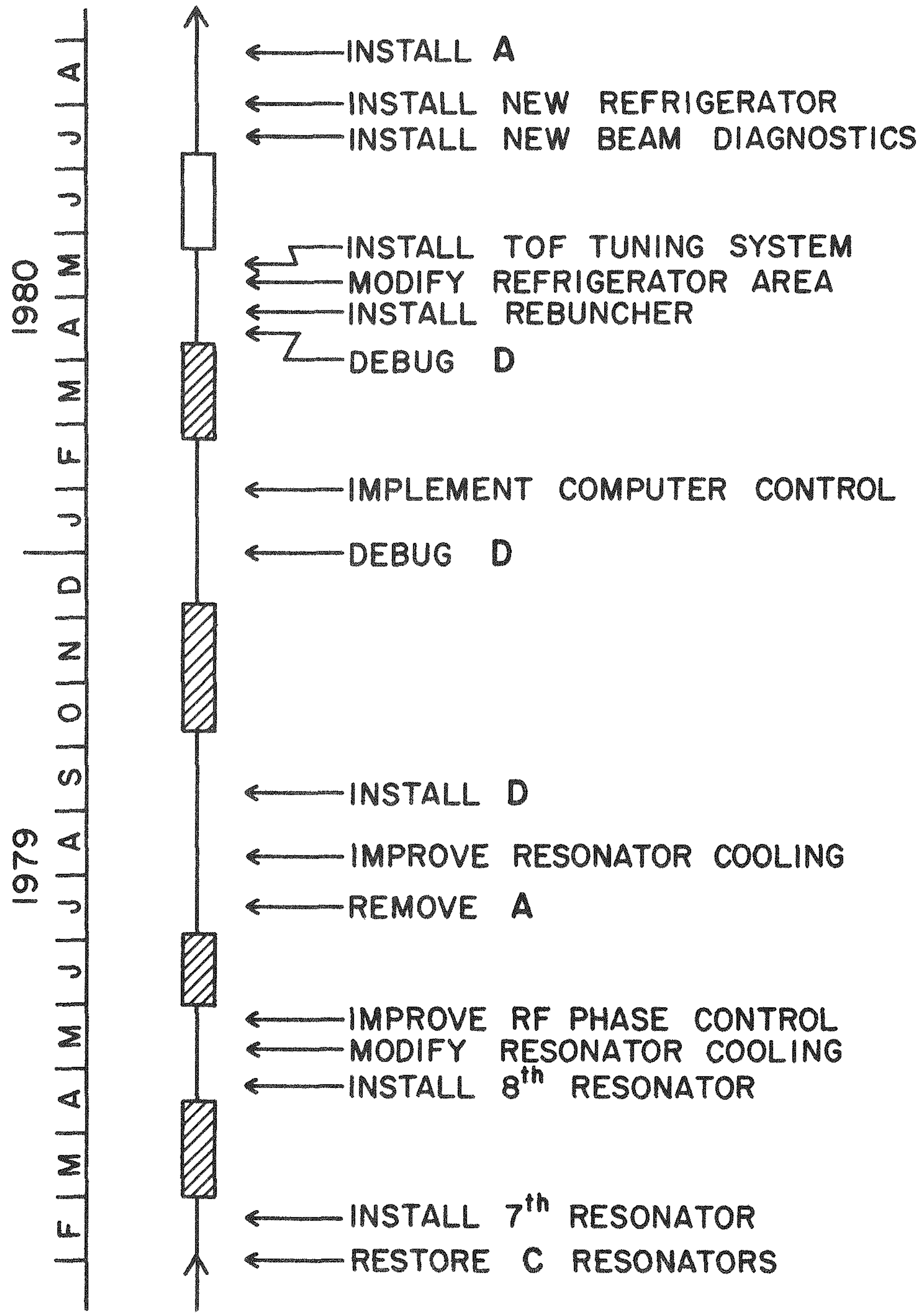

Fig. VI-3. Schedule for operation, improvement, and completion of the booster.

installation of a beam rebuncher, (b) the installation of section A, with 4 low-β resonators, and (c) the installation of the new helium refrigerator. By the end of 1980 the booster will be an excellent accelerator in all respects.

B. INVESTIGATIONS OF SUPERCONDUCTING LINAC TECHNOLOGY

This research program, carried out jointly by the Chemistry and Physics Divisions, is concerned with investigations of the general aspects of applications of superconducting technology to the acceleration of heavy ions. Most of the recent activities have been related to the development of an accelerating structure of the split-ring type made of niobium. Investigations of this type will continue, but the program will gradually be broadened to include developmental work on other aspects of accelerator technology, including the development of superconducting magnets for use in bending and analyzing heavy-ion beams.

1. LOW-β RESONATOR

Sections A and B of the heavy-ion booster require a type of resonator designed to give optimum acceleration for ions with a relative velocity $\beta = 0.06$. The design of a low-β resonator of this kind was started in 1978, and the fabrication of the prototype was completed in late December 1978. During 1979, the first unit was fully and successfully tested, and the fabrication of 6 additional low-β resonators was started. The first of these to be completed was transferred to Florida State University for use as a beam buncher.

By the end of the present reporting period, the design of the low-β resonator has proven to be successful in all respects. In particular, several units have been operated at accelerating fields well above 4 MV/m in off-line tests; and one unit was operated on-line for a period of many weeks at 4.0 MV/m and a power dissipation of 4 W. In all important respects the performance of the low-β design is similar to that of the high-β design.

2. RESONATOR PERFORMANCE

Investigations aimed at understanding and pushing back the limitations on resonator performance are proceeding and are likely to extend over the next few years. During 1979, the emphasis has been on (1) the development of techniques for conditioning superconducting resonators and (2) the study of the stability of resonator performance, especially under beam-line conditions. These topics are, of course, closely related.

The principal advance during the past year has been the demonstration that resonator performance is improved significantly by outgassing the resonators thoroughly prior to cool down. Because of the presence of an indium seal on the resonators, the outgassing temperature must be limited to only about 100°C. Nevertheless, it is found that baking the resonators for two days at this modest temperature provides marked improvements in two respects: (1) it is much easier to burn through the low-field multipacting barriers that are usually present when a resonator is first put into operation and (2) once conditioned, resonator operation is more stable and the operating time available before the unit needs to be conditioned again is much longer. Thus, although the degassing process does not increase the maximum accelerating field, the overall quality of the operation is improved significantly.

The maximum accelerating field continues to be limited by electron loading in which the resonator Q drops rapidly with increasing field. Since this limit can be increased by pulsing a resonator for a long period of time with a 400-W rf amplifier, it seems likely that the speed and perhaps the range of conditioning can be increased by pulsed operation with a more powerful amplifier. A 1500-W amplifier is being acquired to test this idea.

By now we have many thousands of hours of experience with the on-line operation of many resonators, and this is providing quantitative data on performance characteristics. Typically, a resonator can be conditioned off-line to operate at an accelerating field of ∿4.0 MV/m for a power dissipation of 4 watts. When put on line, most units cannot be conditioned to such a high value, but more typically to ∿3.6 MV/m, probably because the fixed input probe used on line does not allow enough rf power to be absorbed.

The long-term stability of units operated on line is somewhat variable and is not well understood. Some units continue to operate at their original high fields for periods of weeks, whereas others decondition toward operation at a somewhat lower level within a few days. Such deconditioned units must then be restored, typically by filling the units with helium gas at a pressure in the range 10^{-5} to 10^{-4} torr and operating at as high a field as can be sustained. This "helium conditioning" procedure typically required about half an hour.

The limit to which a resonator can be conditioned may also vary with time in ways that are not well understood. For example, the limiting fields of five of the six resonators in section C have been unchanged since they were installed in January 1979, even though the cryostat has been warmed up and exposed to air several times. The sixth resonator, by contrast, experienced a sudden and unexplained drop of about 20 percent in its maximum accelerating field.

When all factors that limit performance are taken into account, at the present stage of development the average accelerating voltage that is available for long-term, reliable operation is about 2.9 MV/m. The average can be pushed somewhat higher than this by vigorous conditioning, but frequent breakdown must then be expected. Pushing the average field to the level of 4 MV/m, which is considered a realistic goal, is not expected to be achieved by any single breakthrough in technology but rather by the painstaking removal of numerous small problems. Obviously, this will take time.

3. FAST TUNER

The fast tuner[1] of the resonators is a voltage-controlled reactance (VCX) consisting of a parallel-plate condenser that can be shorted out by a PIN-diode switch. During full-power operation, the VCX must carry about 6 kW of reactive power, a very demanding requirement for the PIN diodes. In the original configuration, six diodes operating in parallel were able to function well for long periods of time, but occasionally one would fail, thus seriously shortening the lifetimes of the remainder. This problem has now been effectively removed by modifying the VCX to have 10 diodes in parallel.

4. RF-PHASE CONTROL

When the booster was first put into operation (1978), the fast tuner VCX did not have enough tuning capacity to control the phase under all circumstances. For example, a momentary breakdown of a resonator could cause mechanical vibrations which in turn induced rf frequency variations too large to control. Because of the large mechanical Q of a cold resonator, such vibrations typically caused the resonator to go out of lock for about a minute.

The phase-control problem has now been solved by using electro-mechanical coupling in the resonator to dampen mechanical motion. The dampening is induced by using the phase-error signal to modulate the rf amplitude, an old idea applied now in two stages:

(a) When the resonator is in lock, the applied amplitude modulation is very small (<0.01%), large enough to provide some dampening but small enough to preserve the beam quality; whereas

(b) when the resonator is out of lock, the amplitude modulation is made strong enough (∿3%) to bring the system back into lock in a few seconds.

When combined with the original VCX, this scheme works so well that resonators rarely go out of lock and then only briefly. The new control feature is now being used routinely for operation of the booster resonators.

5. ENERGY-MEASUREMENT SYSTEM

From the inception of the linac project, it was planned that time-of-flight methods would be emphasized and, in particular, ion-flight time would be used to monitor and to measure beam energy. However, for lack of funds, it has been necessary to delay the implementation of this idea and, as a result, we do not yet have a convenient and/or accurate way to measure the beam energy from the booster.

During 1979, the design and construction of a beam-energy-measurement system was started. The key element of the system is a time-of-arrival detector consisting of a helix resonator excited by the beam. The phase of the induced oscillation indicates the arrival time of the train of beam pulses, and the difference in the phases of two detectors located along the beam line gives a measure of the beam velocity.

The new energy-measurement system will make use of the same techniques used for the phase detector of the bunching system, which has been described in detail elsewhere.[1]

C. PROPOSAL FOR ATLAS

The Argonne Tandem-Linac Accelerator System (ATLAS) is a proposed heavy-ion accelerator[1] to be formed by enlarging the booster and by adding a large new target area, as shown in Fig. VI-4. The resulting system, consisting of the existing tandem and a 7-section linac, will have a performance that is approximately equivalent to that of a 50-MV tandem with two strippers.

ATLAS is aimed squarely at the needs of precision nuclear-structure physics, providing beam energies up to 25 MeV/A, easy energy variability, and beams of exceptionally good quality. The short-pulse character of the beam will be emphasized so as to maximize its usefulness for time-of-flight and other timing measurements. An unusual feature of the facility is the capability of providing beams simultaneously for two independent experiments without a loss of intensity to either.

The ATLAS proposal was reviewed by the Facilities Subcommittee of the DOE/NSF Nuclear Science Advisory Committee (NUSAC) in March 1979, following which the parent committee strongly recommended that the project be funded. Subsequently, the project was originally in the President's Budget for fiscal year 1981 but was eliminated as part of the wave of cost reduction carried out by Congress during the early spring of 1980.

The ATLAS project is being resubmitted for funding in FY 1982. Since the technology involved is now in routine use at the booster and since the booster is demonstrating regularly the unique research capabilities of the technology, the ATLAS proposal is on an even firmer basis now than it was originally.

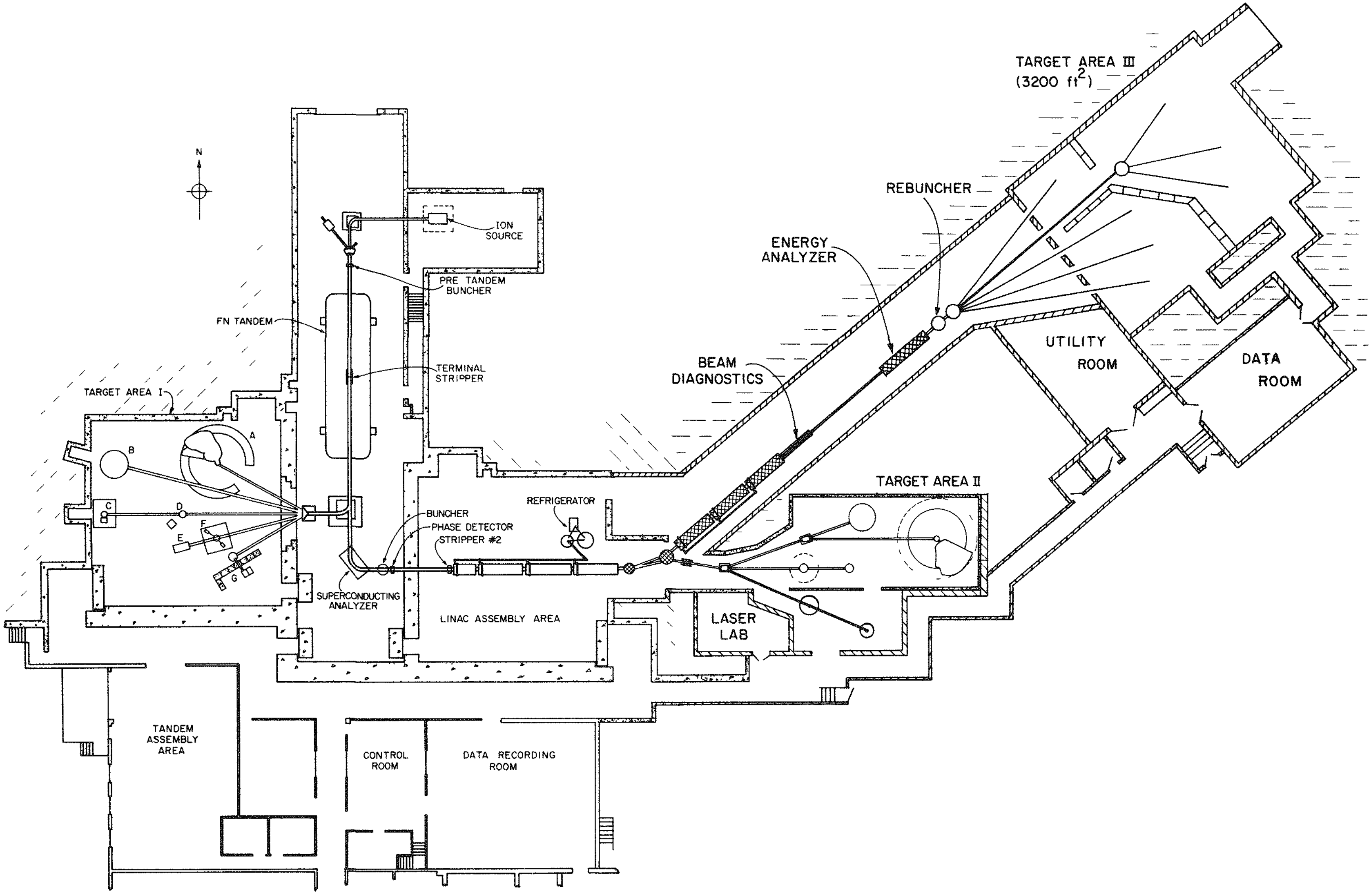

Fig. VI-4. Layout of the proposed ATLAS facility.

VII. ACCELERATOR OPERATIONS

INTRODUCTION

This section is concerned with the operation of both the tandem-linac system and the Dynamitron, two accelerators that are used for entirely different research. Developmental activities associated with the tandem and the Dynamitron are also treated here, but developmental activities associated with the superconducting linac are covered separately in Sec. VI, because this work is a program of technology development in its own right.

A. OPERATION OF THE TANDEM-LINAC ACCELERATOR

The tandem-linac accelerator system provides beams of nuclear projectiles for research in several areas of nuclear physics and occasionally in other areas of science. The accelerator consists of a 9-MV tandem and a partially completed superconducting-linac energy booster. Because of the modular nature of the linac, it can be used effectively to accelerate ion beams before it is completed. In March 1980, the performance of the tandem-linac system is, for ions with mass $A \leq 40$, equivalent to that of a stand-alone tandem with a terminal voltage of about 16.8 MV. During the past year, about 40% of the running time was scheduled for operation of the tandem-linac system and the remainder of the time for use of the tandem alone or for accelerator development. The present status of the booster and its technology are discussed in Sec. VI.

1. RECENT OPERATING EXPERIENCE FOR THE TANDEM

P. K. DenHartog, C. E. Heath, F. H. Munson, Jr., and J. L. Yntema

During 1979, the tandem operated on a seven day/week schedule, except for a three-month period when a five day/week schedule was used in order to expedite beam-line installations. During the period 1 January 1979 through 31 December 1979, the tandem operated 5763 hours. Beams of protons, helium, ^{6}Li, ^{7}Li, ^{12}C, ^{13}C, ^{14}C, ^{14}N, ^{16}O, ^{24}Mg, ^{26}Al, ^{28}Si, ^{32}Si, ^{32}S, ^{34}S, ^{40}Ca, ^{58}Ni, ^{60}Ni were accelerated for the experimental program 91% of the scheduled beam time; 9% of the beam time was used for tandem development and accelerator conditioning.

The tandem operates for long periods of time with voltages in excess of 8.5 MV and with exceptional stability. It is proving to be an excellent injector of the linac.

2. OPERATION OF THE SUPERCONDUCTING LINAC

R. Benaroya, L. M. Bollinger, R. C. Pardo, and K. W. Shepard

During 1979, the linac was used to accelerate heavy-ion beams during three long periods of operation: 6 weeks in March-April, 4 weeks in June-July, and 8 weeks in October-December, a total of 18 weeks. About 24 weeks of operation are planned for 1980. Additional information about the operating schedule is given by Fig. VI-3 of the preceding chapter.

The ions and maximum beam energies accelerated to date (March 1980) are the following: ^{16}O at 140 MeV, ^{28}Si at 166 MeV, ^{32}S at 232 MeV, and ^{34}S at 196 MeV. This performance is approximately equivalent to that of a 16.8-MV tandem with two strippers. The upper energy limits are being increased steadily by adding more resonators. Also, the present limit of about $A \leq 40$ on the mass for effective acceleration (set by the length of the high-β resonators now in use) will soon be extended by adding several shorter resonators.

Overall, the booster is proving to have the versatility, reliability, and usefulness that were expected of it.

3. UPGRADING OF THE TANDEM

P. J. Billquist, P. K. DenHartog, C. E. Heath,
F. H. Munson, Jr., and J. L. Yntema

During 1979, no major modifications to the accelerator were made. Rather, the effort was devoted to various refinements, some of which are detailed below.

a. Ion Sources

The injection system has three ion-source positions. One position is occupied by the direct-extraction duoplasmatron, the second by the Li-exchange source, and the third is the 150-kV injection system occupied by the Florida State type of sputter source, which is used to provide a beam for injection into the linac.

A temporary experimental off-line test stand has been assembled and put into operation, and design work on a permanent test facility has been completed. The test stand has been used (1) to test sputtering sources prior to installation on the tandem injection system, (2) to test design modifications intended to improve source characteristics (emittance and intensity), (3) to test various surface conditions in order to establish the best combination of sputtering coefficient and Cs dwelling time, and (4) to modify the source optics. The test stand has also been used to obtain experience with an Aarhus-type source and to modify this source to improve its reliability.

Improved power supplies and control circuits for the ion-source system have been built and brought into operation. This apparatus allows control of the source parameters both at the source and from the control room and has resulted in a considerable improvement in the overall performance of the tandem.

Our proficiency in using small quantities of material in the ion source has improved substantially in the past year. For example, a pellet of only 100 mg of isotopically enriched ^{64}Ni mixed with either high-purity Al or Zn yields an analyzed beam of about 0.5 μA of $^{64}Ni^{10+}$. Similarly, a small pellet pressed from FeS in which the sulfur is 4% ^{34}S yields an analyzed beam of 0.2 μA of $^{34}S^{8+}$.

b. Development of the Terminal

A number of tasks designed to enhance the capabilities of the terminal have been undertaken.

The all-metal valves installed in the terminal in late 1978 have worked well. The valves have been operated more than 25 times without any apparent damage to the valve seats. The successful operation of these valves has made it unnecessary to bake the accelerator tubes during the past year. Apart from the potential danger to the accelerator tube, baking involves a time loss of at least four days for every bake-out operation.

The remote-control system for the gas inlet of a short stripper canal has been completed.

Tests on fiber optic lines to the terminal and survival tests on electronic components both at the base of the accelerator and in the terminal were completed.

The ion pump in the terminal was placed in operation, with a remote readout of the terminal pressure. Terminal pumping has resulted in an improvement by a factor of 40 in the terminal vacuum under static conditions.

A multiplexer to minimize the number of fiber-optic cables running along the column has been constructed, and an improved control system for the foil changer is being designed.

c. Stripping Foils

The performance of several kinds of carbon stripping foils in the tandem terminal has been studied by measuring the foil lifetimes, beam transmission and, in some cases, energy straggling. Normal carbon foils and special foils made by several groups (University of Arizona, ORNL, and NSF-Harwell) were compared.

The lifetimes of some of the special foils were considerably longer than normal, but the energy straggling for some of these was so large that the foils were not useful as strippers. For all of the longer-lived foils, the tandem transmission for heavy ions decreased with time. The rate of decrease in transmission increases with the atomic number of the ion beam. Experiments are in progress to establish the cause of the decrease of transmission and to eliminate it, if possible.

d. Energy-Loss Straggling in Thin Carbon Stripper Foils

W. Henning, P. K. DenHartog, and J. L. Yntema

The energy-loss straggling in thin carbon stripper foils (2 to 30 $\mu g/cm^2$) was measured by a high-resolution time-of-flight method in which the tandem-linac picosecond beam-bunching system is used. This work is of interest because energy-loss straggling in stripper foils largely determines the longitudinal phase space $\Delta E \Delta t$ of the linac beam.

In our straggling measurements, the tandem-linac system was operated with either the linac turned off, thus providing for a 17 m flightpath between the buncher and detector, or with the last resonator operating as a rebuncher $\approx$4 m before the target, in order to determine the time resolution of the detector system. Bunched ^{16}O and ^{32}S beam pulses were focused onto a gold target behind the linac, and the time distribution was measured by detecting scattered ions in a Si surface-barrier detector. Examples of data are given in Fig. VII-1. Here the inner curve is the system resolution, as measured with the short flightpath for a 50-MeV ^{16}O beam, and the outer curve is the time distribution for a 5-$\mu g/cm^2$ foil that is specially prepared for extra-long lifetime, as measured with the full flight path. The corresponding energy spread is determined from the measured time width.

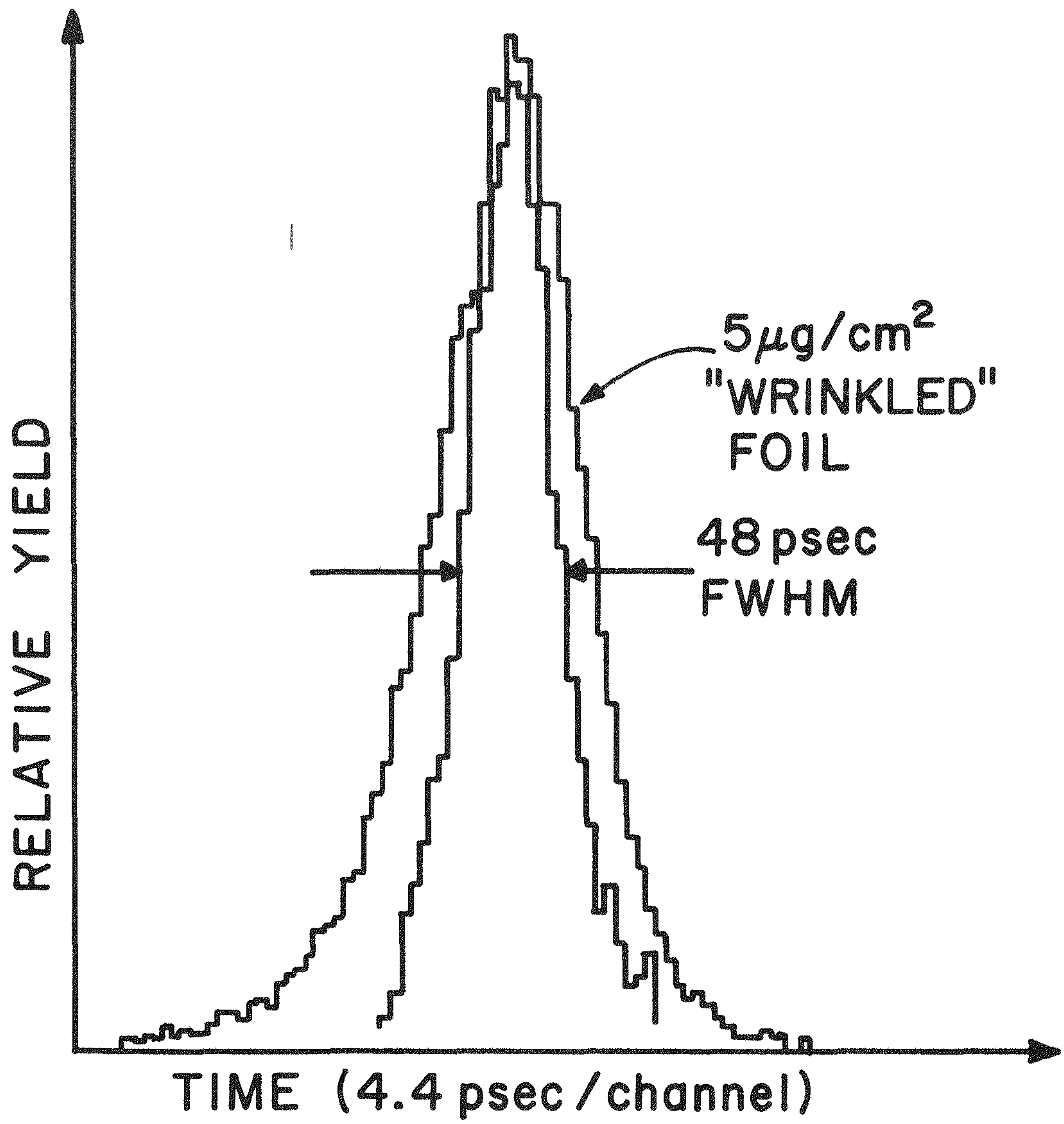

Fig. VII-1. Time spectrum of the pulsed beam for a 5 μg/cm^2 "wrinkled" stripper foil in the tandem terminal. The 48 psec FWHM is the measured system resolution. The beam was ^{16}O at 50 MeV.

4. INSTALLATION AND IMPROVEMENT OF THE BOOSTER

R. Benaroya, L. M. Bollinger, R. C. Pardo, K. W. Shepard, J. Aron,*
B. E. Clifft,* K. W. Johnson,* P. Markovich,* and J. M. Nixon*

The main report on the linac is given in Sec. VI.

a. Linac Section A

The installation of additional major parts of the booster is proceeding steadily during those periods of time when the booster is not being operated. A principal addition planned for 1980 is linac section A, which will have four low-β resonators. These resonators will extend the mass range for effective acceleration up to the nickel ions, at least.

b. Linac Section B

The construction of linac section B and its associated cryogenic equipment has started. Resonators and the cryostat are under construction, and the helium refrigerator needed to cool the accelerator section has been ordered.

The new refrigerator, which will be installed in late 1980, has a cooling capacity of about 200 watts initially and an ultimate capacity of at least 275 watts, when a third compressor is added. The new refrigerator will operate in parallel with the present 95-watt refrigerator. The added cooling capacity will have an immediate benefit for the booster, whose accelerating power is now limited somewhat by the available cooling capacity.

c. Beam Rebuncher

A superconducting resonator designed to rebunch or to debunch the beam from the booster will be installed on the output beam line in April 1980. This addition will greatly enhance the research capability of the accelerator system by allowing its short-pulse characteristic to be used to full advantage.

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*Chemistry Division, ANL.

d. Linac Tuning

One of the greatest limitations connected with the use of the booster has been the fact that the technique used to tune the resonators, although effective, has been rather time consuming. As a result, we have tried to minimize the number of times that the linac is tuned, and this has often led to operation of the accelerator system under less than optimum conditions. A new tuning system designed to eliminate this problem is under construction. With this system we expect to be able to tune a resonator in a minute or two, a short enough time to allow operating conditions always to be optimized to the experimental needs.

e. Measurement of Beam Energy

Another operating problem has been that, until now, we have had no way to measure the beam energy accurately. An experimental system designed to measure the energy by means of a time-of-flight technique is under development and will be in operation by late 1980. It is expected to measure the beam energy continuously and nondestructively with an accuracy of a few parts per 10^4. This capability will enhance immensely the overall quality of the operation of the accelerator.

5. EXPERIMENTAL SYSTEM ASSOCIATED WITH THE HEAVY-ION BOOSTER

The system of experimental apparatus for use with the beam from the booster began to take form during 1979. None of the major pieces of equipment have been completed, but several are far enough along to be useful for research by the end of this reporting period (March 1980). The experimental system will be developed steadily throughout 1980.

The small target room being used for research with the booster beam will be expanded by about 900 ft^2 in early 1981. This added space will greatly increase the usefulness of the research area, which is extremely crowded now, as seen in Fig. VII-2.

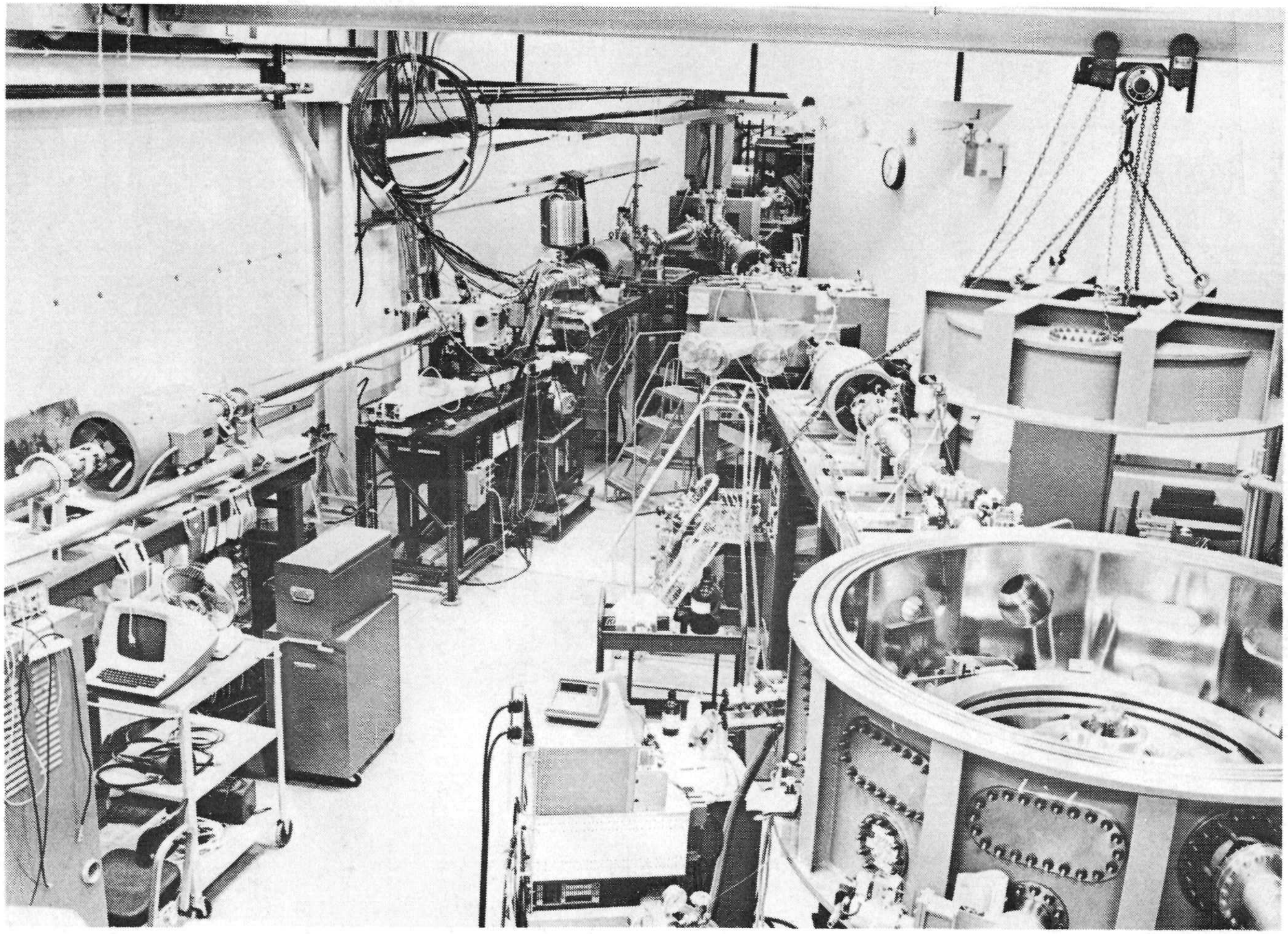

Fig. VII-2. Photograph of beam lines and experimental stations located in the experimental area associated with the linac.

a. Installation of Beam Lines in the Linac Experimental Area

D. G. Kovar, W. F. Evans, J. W. Lamka, J. N. Worthington, J. J. Bicek, and C. E. Bolduc

During 1979, much progress was made in completing the experimental area associated with the superconducting linac booster. The zero-degree beam line, which has two experimental stations (an 18-in. scattering chamber and a gamma-ray station), was completed in time for the October-December (1979) linac running period. The 19-degree beam line to the new 65-in. scattering chamber was installed in March 1980. Shown in Fig. VII-2 is a photograph of the linac experimental area taken in April 1980. The 65-in. scattering chamber was used in experimental measurements during the linac running period in March 1980, as were the experimental stations on the zero-degree beam line. Designs for the spectrograph beam line have been completed and most components have been purchased. This beam line is expected to be installed and the Enge split-pole magnetic spectrograph made operational in early 1981.

b. 65-in. Scattering Chamber in the New Target Area

W. Henning, D. G. Kovar, and J. N. Worthington

The 65-in. stainless-steel general-purpose scattering chamber in the linac annex (see Fig. VII-3) has been put into operation and used successfully in experiments with beams from the superconducting linac. Absolute fusion cross-section measurements at forward angles have made use of the high angular precision which is a result of the direct-drive, direct-readout scheme of the angular motion of the detector rings. At present, 3 detector rings have been installed, with the fourth planned for installation later this year. The auxiliary target position near the entrance port has been very useful in coincidence measurements between x rays and fusion evaporation residues. Improvements in detector mounts, collimator system, pumping speed and remote control via microprocessor are now underway. The scattering chamber is expected to be heavily used in time-of-flight measurements after installation of the superconducting rebuncher, which is scheduled for the late spring of 1980.

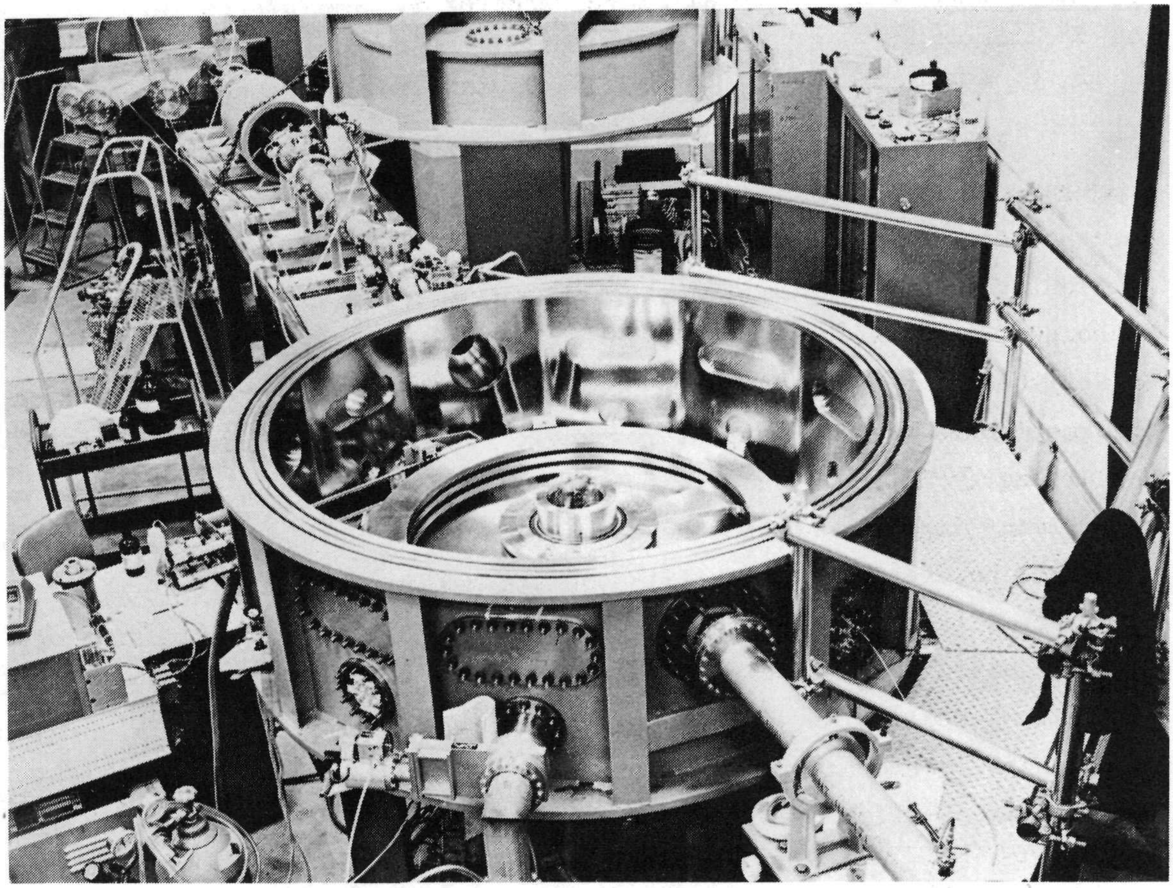

Fig. VII-3. 65-in. scattering chamber.

c. Split-Pole Magnetic Spectrograph in the Linac Experimental Area

D. G. Kovar and J. R. Erskine

The Enge split-pole magnetic spectrograph from the ANL cyclotron was installed in its position in the experimental area associated with the linac booster in early 1979. Designs for the spectrograph beam line are in their final stages and most of the components have been purchased. It is now planned that the beam line will be installed and the spectrograph made operational by early 1981. The spectrograph will be activated without major redesign (at this time) of the existing system.

d. Improvements on the Focal-Plane Detector System for the Magnetic Spectrograph

D. G. Kovar, J. C. Stoltzfus,* S. J. Sanders, J. E. Kulaga, and M. Paul

Work was completed in 1979 on an effort to use two position measurements by the focal-plane detector[1] of the ANL split-pole magnetic spectrograph to establish the trajectory of a detected particle. In particular, suitable computer programming, together with a calibration technique, was developed to obtain angle information from the trajectories established by the position measurements. In its present mode, the angle information is used to correct for angle effects in the measured differential energy losses ΔE and in the total E_{total}; both corrections can make significant improvements in the identification of mass and charge Z. More powerful, however, is the ability to make multiangle measurements and to construct virtual focal planes appropriate for the various reaction products so as to obtain high-resolution spectra for each. With the identification of the trajectories, it is now possible to correct for the differences in path lengths and hence flight times. We plan to use this capability in making time-of-flight measurements with the beams from the linac booster.

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*Beloit College, Beloit, Wisconsin.

[1] J. R. Erskine, T. H. Braid, and J. C. Stoltzfus, Nucl. Instrum. Methods 135, 67 (1976).

e. γ-Ray Sum Spectrometer

T. L. Khoo, S. Levenson,* I. Ahmad,† J. Borggreen, P. Chowdhury, S. R. Faber,‡ and R. K. Smither

A sum spectrometer for measuring the total γ energy released in a reaction has been constructed. The sum energy makes it possible to differentiate between reaction channels and also to select states with different angular momentum origin. The spectrometer has already been used with success in several experiments (see Sec. II.C, High Angular Momentum States in Nuclei).

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*Thesis student, University of Chicago, Chicago, Illinois.

†Chemistry Division, ANL.

‡Purdue University, W. Lafayette, Indiana.

The spectrometer consists of two independent 13-in. × 6-in. NaI crystals, each segmented into four optically separate quadrants. Bores of $1\frac{1}{4}$-in. i.d. axially and 3-in. i.d. along a diameter allow for entrance and exit of the beam and viewing of the target by two or more Ge(Li) detectors. The detectors are supported in a manner which makes it very easy to vary their distance and angle with respect to the target.

A stabilization system based on an LED coupled to the photomultipliers via optic fibers will soon be implemented; control of the high voltage supply by CAMAC will also be part of the stabilization system. Hardware and software refinements in data acquisition with the sum spectrometer will also be made.

f. γ-Ray Facility

R. K. Smither, T. L. Khoo, I. Ahmad,* J. Borggreen, W. Kutschera, and J. N. Worthington

The γ-ray facility is now fully operational. The beam line, beam diagnostics, pumps, apertures, target chambers, and detector holders have been installed and used in several experiments already. Three target chambers are available, all of which fit inside the NaI γ sum spectrometer; with one of these chambers, the beam can be dumped downstream of the target.

The detector support system revolves around a steel post anchored to the floor beneath the target position. Two Ge(Li) detector holders pivot around this post, allowing accurate angular and radial positioning. The two NaI crystals of the sum-spectrometer crystals slide independently on two Thompson rods, which are attached to a secondary post which revolves within the main support post. Thus the radial positions and horizontal orientation of the crystals are controlled with extreme ease. In the design, care has been taken to keep the mass around the target chamber to a minimum in order to minimize scattering of γ rays and neutrons.

Supports for a second pair of Ge(Li) detectors and two large 10-in. × 12-in. NaI crystals will soon be added. In addition, a new chamber capable of holding particle detectors inside the sum spectrometer will be designed. Planning is also underway for an electron spectrometer consisting

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*Chemistry Division, ANL.

of a lens to focus electrons onto a Si(Li) detector, a five-crystal intrinsic Ge polarimeter, and an anti-Compton shield for Ge(Li) detectors.

g. Nuclear Target Making and Development

G. E. Thomas

The Physics Division has a facility which produces very thin targets for experiments at the Tandem and Dynamitron accelerators, for experiments of other members of the Division, and any other division at the Laboratory needing this service.

This year, the target-making facility produced more than 1000 targets, as in the past, varying in thickness from a few monolayers to several mg/cm^2. The different element isotopes or compounds evaporated, rolled, anodized, or oxidized included Al, Au, Al_2O_3, $^{10,11,nat.}B$, $^{40,42,44,48}Ca$, CaF_2, ^{65}Cu, deuterated poly, $^{6,nat.}LiF$, 24,25,26Mg, MgO, NaCl, ^{143}Nd, $^{58,nat.}Ni$, Pb, Pt, Rn, $^{144,149,150,152,154}Sm$, $^{120,122,124}Sn$, ^{122}Te, $^{46,nat.}Ti$, V, ^{170}Yb, Zn, and pellets of $K_2{}^{32,nat.}SiF_6$ using either high purity Al or Zn as a binder.

Targets consisting of several layers of different thin targets placed together to produce one composite target have been made for different experiments.

A technique has been developed to routinely produce the previously difficult self-supporting 50 μg/cm^2 $^{10,11,nat.}B$ targets.

Experiments now usually demand higher purity targets than in the past. As a result, we have performed experiments to determine the optimum evaporation parameters to produce the purest targets.

6. OUTSIDE USERS OF THE TANDEM-LINAC ACCELERATOR SYSTEM

Outside users have played an important role in research at the tandem since its original installation in 1962. Now, with the advent of the superconducting heavy-ion energy booster, new groups have begun to use the accelerator system. In addition, a group from Florida State University is getting seriously involved in the use of our superconducting-linac technology.

University Use of the Tandem As a Stand-Alone Accelerator

The development of the superconducting linac as an ion-energy booster and its use as a source of energetic heavy ions for experiments consumed a large fraction of the tandem time during calendar year 1979. Nevertheless, many scientists from outside institutions have continued to use the tandem alone in their research programs. During the year, fifteen investigators from eleven institutions came to Argonne to use the tandem. Most of these efforts are collaborations, though this is a matter of convenience, not policy.

Outside users worked on experiments that represent 27% of the total research time scheduled on the tandem. A list of those institutions from which visiting scientists came in 1979 is given below. Included in the list are the names of the visiting scientists, their Argonne collaborators (enclosed in parentheses), and the title of the research done. All university use of the tandem is included here—not only heavy-ion research.

(1) Beloit College
Development of a Focal-Plane Charged-Particle Detector for the Split-Pole Spectrometer
J. C. Stoltzfus, (D. G. Kovar, M. Paul, and S. J. Sanders)

(2) University of Birmingham, England
Three Nucleon Transfer Reactions on ^{11}B
G. C. Morrison, (D. F. Geesaman, W. F. Henning, D. G. Kovar, C. Olmer, and B. Zeidman)

(3) University of California, Berkeley
A Determination of the Mass of ^{106}In
J. Äystö, (C. N. Davids, and B. Filippone)

(4) University of Chicago
Two- and Three-Electron Spectra of Chlorine
R. DeSerio, (H. G. Berry, and T. J. Gay)

(5) University of Kansas
Study of γ-Ray Yields for the $^{16,18}O + ^{24,26}Mg$ Reactions
F. W. Prosser, Jr., R. Racca, (C. N. Davids, and D. G. Kovar)

(6) University of Michigan
A Determination of Hydrogen-Depth Profiles in Metals by Using Heavy Ionic Probes
A. Hanson, D. Vincent, (C. N. Davids, and M. J. Murphy)

(7) Northwestern University
A Study of the Properties of the Giant Dipole Resonance by Radiative Capture of Alpha Particles
R. E. Segel, J. V. Maher,† and (L. Meyer-Schützmeister)

†University of Pittsburgh, Pittsburgh, Pennsylvania.

(8) University of Pittsburgh
A Study of the Properties of the Giant Dipole Resonance by Radiative Capture of Alpha Particles
J. V. Maher, R. E. Segel,† and (L. Meyer-Schützmeister)

(9) Purdue University
A Study of the Properties and Calibration of a Counter System for High-Energy Physics
R. P. Scharenberg, A. S. Hirsch, and B. C. Stringfellow

(10) Western Michigan University
Gamma-Ray Studies in ^{45}V
G. Hardie, (A. J. Elwyn, S. A. Gronemeyer, and L. Meyer-Schützmeister)
The Beta Decay of ^{45}V
G. Hardie, (A. J. Elwyn, S. A. Gronemeyer, and L. Meyer-Schützmeister)

(11) Yale University
Single-Nucleon Transfer Reactions Induced by ^{12}C on ^{48}Ca at 45 MeV
R. Peterson, (W. F. Henning, D. G. Kovar, M. Paul, and S. J. Sanders)

Resident Graduate Student Program

The Resident Graduate Student Program continues to appeal to aspiring doctoral candidates. During the year four students finished their thesis research and have taken other jobs. Students participated in experiments which used 39% of the time allotted for physical research. The following is a list of students participating in the Resident Graduate Student Program who did research at the tandem during the past year. Their home institutions and local advisors are also given. Those who received their doctoral degree during the year are indicated by an asterisk.

(1) K. Daneshvar,* University of Illinois, Chicago Circle
D. G. Kovar, adv.

(2) A. R. Davis, University of Chicago
J. P. Schiffer, adv.

(3) B. Filippone, University of Chicago
C. H. Davids, adv.

(4) S. A. Gronemeyer,* Washington University
L. Meyer-Schützmeister, adv.

(5) S. M. Levenson, University of Chicago
J. P. Schiffer, adv.

(6) M. J. Murphy,* University of Chicago
C. N. Davids, adv.

†Northwestern University, Evanston, Illinois.

University Participation in Linac Experiments

Although the beams from the superconducting linac booster have been available for experiments only on an occasional basis (total of 18 weeks), the facility is already being used by outside users. In particular, the group of P. J. Daly at Purdue University is engaged in a very active collaboration in which several graduate students come regularly to Argonne and one postdoctoral research associate, supported by Purdue, is resident here. As the booster becomes operational on a more regular basis, the participation of university users is expected to increase, and we shall encourage this.

A list of institutions from which visiting scientists came in the past year follows. Included in the list are the names of their Argonne collaborators, enclosed in parentheses, and the title of the research done.

University of Kansas

Measurement of the Inclusive Alpha-Particle Yields Produced in $^{16}O + ^{40}Ca$ at $E_{lab}(^{16}O) = 120$ MeV

F. W. Prosser and R. Racca (D. G. Kovar, C. N. Davids, D. F. Geesaman, M. Paul, and S. J. Sanders)

University of Maryland

^{16}O, ^{32}S Induced Fission on Rare Earth Targets

A. Mignerey and J. M. Lebowitz† (B. B. Back,‡ R. R. Betts,‡ W. Henning, and K. Wolf‡)

Purdue University

Study of High Angular Momentum States in Nuclei by Gamma Spectroscopy

P. J. Daly, C. L. Dors, S. R. Faber, and J. Wilson (I. Ahmad,† J. Borggreen, P. Chowdhury, C. N. Davids, T. L. Khoo, W. Kutschera, S. Levenson, and R. K. Smither)

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†Brooklyn College, Brooklyn, New York.

‡Chemistry Division, ANL.

B. DYNAMITRON OPERATIONS

The Physics Division operates a high-current 4.5-MV Dynamitron accelerator which has unique capability as a source of ionized beams of most atoms and many molecules. Among the unusual facilities associated with the Dynamitron are (1) a beam line capable of providing "supercollimated" ion beams permitting angular measurements to accuracies of 0.005 degree, (2) a beam-foil measurement system capable of measuring lifetimes of a few picoseconds, (3) an experimental system dedicated to measuring absolute nuclear cross sections at low energy, (4) a precise angular-correlation system for weak-interaction studies, and (5) a simultaneous irradiation system by which heavy ions from the Dynamitron and helium ions from a 2-MV Van de Graaff accelerator are focused on the same target. An advanced PDP-11/45 computer system is used for on-line data analysis and for the control of experimental systems.

1. OPERATIONAL EXPERIENCE OF THE DYNAMITRON

A. J. Elwyn, F. P. Mooring, R. L. Amrein, and A. E. Ruthenberg

The Dynamitron continued to perform well during the past year. The normal operating schedule was twenty-four hours a day, five days a week. Very little running was done on weekends during calendar year 1979.

During the year the accelerator was staffed a total of 5934 hours. Of this time 5451 hours (92%) were scheduled for experimental research during which a beam was provided to the experimenters 86% of the time. Machine preparation time used up 4% of the scheduled research time and machine malfunctions the remaining 10%. Scheduled accelerator improvements and modifications used a total of 459 hours or 8% of the total available time.

The great versatility of the Dynamitron continued to be exploited by the research staff. Ion currents on target varied from less than a nanoampere to about 25 microamperes with the ion energies ranging from 0.35 MeV to 3.7 MeV. A wide range of both atomic and molecular ions were delivered on target. They included $^{1}H^{+}$, $(^{1}H_2)^{+}$, $^{2}H^{+}$, $^{4}He^{+}$, $(^{4}He_2)^{+}$, $^{4}He^{+}$, $^{4}He^{++}$, $(^{4}HeH)^{+}$, $^{7}Li^{+}$, $^{12}C^{+}$, $(^{12}C^{1}H)^{+}$, $^{14}N^{+}$, $^{16}O^{+}$, $(^{16}O^{1}H)^{+}$, $(^{16}O^{1}H_2)^{+}$, $^{20}Ne^{+}$, $(^{12}C_2{}^{1}H_3)^{+}$, $(^{12}C^{16}O)^{+}$, $(^{14}N_2)^{+}$, $(^{12}C_3{}^{1}H_3)^{+}$, $^{40}Ar^{+}$, $^{40}Ar^{+++}$, $^{52}Cr^{+}$, $^{56}Fe^{+}$, $^{58}Ni^{+}$, $^{84}Kr^{+}$, $^{132}Xe^{+}$.

During the year a total of 59 investigators used the Dynamitron in some phase of their experimental research. Of these, 23 were from the Physics Division, 20 were from other Argonne research divisions, 10 were outside users (not temporary appointees) from other research facilities, and 6 were members of the Resident Graduate Student Program. Of the scheduled time, 69% went to members of the Physics Division, 19% to other Argonne divisions, and 12% was exclusively assigned to outside users. However, outside users collaborated in experiments that used 30% of the total available time, and participants in the Resident Graduate Student Program worked on experiments that used 29% of the time.

No major difficulty—mechanical or electrical—occurred during the past year to significantly hamper experimental activity at the facility. Most maintenance work was of a normal routine nature. In order to forestall any serious arc damage of the sort that occurred about a year ago (described in last year's report), the machine was opened up for about a week during the summer so that the Plexiglas mainframe could be examined in detail. All parts mounted on the frame including the rectifiers were removed, and the frame was thoroughly inspected and cleaned. Minor spark damage was repaired. Subsequent machine operation up to a voltage near 3.7 MeV has proved to be relatively spark free.

The on-line IMSAI 8080 microcomputer has been operated routinely for mass scans and, in a limited manner, for the logging of various accelerator parameters read off the control panel of the machine. The use of the computer to record routinely these parameters (rather than have the operators manually write down the numbers in a log book) is expected to be initiated during the present year. The fiber-optics light-link system for monitoring the accelerator parameters within the high-voltage terminal, designed by National Electrostatic Corp., should be delivered shortly, and installation and testing will be started.

During the past year, a program to develop ion sources for the acceleration of beams of Li, Be, and B as well as their hydrides, was initiated. Up to now only limited success has been obtained. By employing a thermionic emission source based on a successful design in operation at the University of Lyon, in France, analyzed $^{7}Li^{+}$ beams of up to 2 μamp have been accelerated. However, no lithium hydride ions have as yet been identified. Further development will continue during the present fiscal year. The ion-source test bench was utilized to obtain 0.2 to 0.3 μamps of $^{4}He^{++}$ ions from an rf ion source coupled to a mass selector. It is hoped that with further development larger currents of doubly-charged ^{3}He and ^{4}He ions can be obtained.

Because of the research needs of the two major atomic physics experimental-group users of the Dynamitron, a project has been initiated to upgrade the energy of the accelerator to the vicinity of 5 MV. The following changes have been proposed and are starting to be implemented: (1) The pressure of the SF_6 insulating gas in the pressure vessel will be increased from 90 psig to 135 psig. A new storage tank to be connected in series with the present one will be located outside in the area near the shield wall. (2) An SF_6 on-line gas purifier will be bought and installed via connecting pipes to the pressure vessel. Future modifications to the present antiquated gas-handling system are being considered. (3) New single-piece Plexiglas supporting-frame members have been ordered to replace the present deteriorating jointed members. (4) A new toroidal coil assembly frame has been ordered to provide adequate high-power operation at 5 MV. Rebuilding the transformer using the pie-shaped coils in our possession will be done here. (5) It is not yet known whether new solid-state rectifiers will be necessary for the higher-voltage operation, although it is expected that a modification to the present rectifier configuration may be needed. Dr. Alexander Langsdorf, who is the person most responsible for the excellent past performance of the Dynamitron and who is now retired from the Physics Division, has agreed to serve as a consultant on this project.

The radiation monitoring and interlock system on the accelerator is presently undergoing modification in order to adhere more closely than in the past to guidelines set up by the Occupational Health and Safety Division. The system consists of two principal components: (1) Electronic and mechanical hardware to provide safety information to personnel and to remove the accelerator beam from an area in the event of unsafe conditions. (2) Administrative controls to provide assurance that appropriate startup procedures are used, the bypassing of the safety hardware is conducted in a safe manner, and that all personnel are made aware of the proper safety regulations. The administrative controls are now in effect and modifications to the existing hardware are in the process of being implemented.

2. UNIVERSITY USE OF THE DYNAMITRON

F. P. Mooring, A. J. Elwyn, and R. L. Amrein

During calendar year 1979 scientists from outside the laboratory continued to use the Dynamitron and its associated facilities in their research programs. Some came for only a single experiment but most have ongoing programs based on the availability of the accelerator to them. As in the past most of the visiting scientists collaborated with local investigators, but a few worked independently. The choice is one made by the outside user.

During the year eleven scientists came from six outside institutions. Of the total time scheduled for experiments, 30% was allotted to groups which included visitors from other laboratories. A list of those institutions for which time on the Dynamitron was scheduled during 1979 is given below. The list includes the name of the institution, the title of the research done, and the names of the principal investigators. The names of local collaborators are enclosed in parentheses.

(1) University of Chicago
Heavy Ion Beam Foil Spectroscopy
R. DeSerio, (H. G. Berry, R. Brooks, T. J. Gay, and W. J. Ray)

(2) University of Illinois
A Study of the Rate Dependence of Gain Shifts of Large NaI Crystals
A. M. Nathan, (T. J. Bowles, C. Gagliardi, and R. D. McKeown)

(3) Los Alamos Scientific Laboratory
A Study of the Time Spectrum of the Ion Beam from the Dynamitron
T. J. Bowles, S. J. Freedman,* (A. R. Davis, C. Gagliardi, G. T. Garvey, R. D. McKeown, and B. Myslek-Laurikainen)

(4) Marquette University
Radiation Damage of Covalent Crystal Structures
L. Cartz, R. Fournelle, A. Gowda, F. G. Karioris, C. H. Ma, K. Ramasami, and G. Sarkar

(5) Stanford University
A Study of the Time Spectrum of the Ion Beam from the Dynamitron
S. J. Freedman, T. J. Bowles,* (A. R. Davis, C. Gagliardi, G. T. Garvey, R. D. McKeown, and B. Myslek-Laurikainen)

Five members of the Resident Graduate Student Program made use of the Dynamitron during the past year. Altogether they participated in experiments which used 29% of the scheduled time. Three performed a principal part of their thesis project at the accelerator. Those using the machine during the year are listed below, together with their home institution and their local thesis advisor. Those who completed their thesis research during the year are indicated by a dagger.

(1) C. A. Gagliardi, Princeton University
G. T. Garvey, adv.

(2) T. J. Gay, University of Chicago
H. G. Berry, adv.

(3) A. R. Davis, University of Chicago
J. P. Schiffer, adv.

(4) S. Levenson, University of Chicago
J. P. Schiffer, adv.

(5) R. D. McKeown,† Princeton University
G. T. Garvey, adv.

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*From another outside institution.

VIII. GeV ELECTRON MICROTRON

INTRODUCTION

A strong consensus has developed recently in the nuclear physics community that research with electromagnetic probes in the 1—2 GeV range generated by a high current 100% duty factor electron accelerator represents an exciting new frontier. Because of this rapidly growing interest, a design group of 5 ANL physicists and accelerator specialists recently reviewed developments in accelerator technology and developed conceptual designs for technical evaluation and subsequent cost analysis. Exploratory designs were developed for two concepts, the linac-stretcher ring and a modified microtron system. These were used to make a critical comparison of the two conceptual designs along with an improved microtron design, the double-sided microtron. The results are presented in Table VIII-I. The "double-sided" microtron shows promise for development into a substantially less expensive facility than a linac-ring system, but its technical feasibility remains to be established. The potential savings in capital cost are large for the microtron system, perhaps $10 million. They dictate that in the absence of a major technical limitation the double-sided microtron is the preferred design.

One of the major technical questions is whether magnetic guide fields of the requisite stability and precision are attainable in a 1—2 GeV accelerator. To resolve this question we are carrying out an engineering study and design of the basic segment magnet for a 2-GeV double-sided microtron. Because of the strong vertical defocusing forces present at orbit entry and exit from a magnet of typical design, it is necessary to configure and determine the fringe fields accurately and establish a system of additional focusing elements which will ensure orbit stability and high beam transmission. A detailed design of an appropriate segment magnet is planned to be followed by construction of a prototype of the portion of a segment magnet corresponding to the fields traversed in the first 6 turns of beam operation in a 2-GeV accelerator, i.e., 50—300 MeV. Field measurements will be made and compared with assumptions used in the preliminary design studies. Pending confirmation of orbit stability, a complete prototype will be constructed. Orbit calculations and beam breakup analysis based on the measured field configurations will also be carried out.

In the course of the preliminary study of possible technical alternatives for the design of a GeV electron accelerator, several questions were raised which could be addressed in specific short research and development projects. Although the decision was made to pursue the microtron design, it is important that these questions be answered in order that the relative technical merit of the various alternatives be clearly established. These projects will be completed in 1980.

TABLE VIII-I. Comparison of accelerator designs.

Characteristic	Linac ring	Microtron	Bicyclotron*
Beam quality, $\Delta E/E$ emittance	$\gtrsim 10^{-3}$ $\lesssim 0.2\ \pi$ mm-mr	$\gtrsim 10^{-4}$ $\lesssim 0.1\ \pi$ mm-mr	$\gtrsim 10^{-4}$ $\lesssim 0.1\ \pi$ mm-mr
Beam current blowup limit	$\sim$600 μamp	$\sim$100—500 μamp (computer study)	$\sim$100—500 μamp (computer study)
Multiple beam capability	yes	with external beam splitter	with external beam splitter
Multiple beam energies	no	to be studied	to be studied
Capital cost	$25M3	$20M9	$15.6M
Power, AC (2-GeV operation)	6.4 Mw	4.2 Mw	4.2 Mw
Scaling law, capital cost (leading term)	$\sim E$	$\sim E^3$	$\sim E^3$
Flexibility of design for increased energy	excellent	poor	underdesign of magnet and linac required

*Double-sided microtron.

a. Study of Beam Breakup in SLAC Type Linear Accelerators

Current conceptual designs for 2-GeV linac-stretcher ring systems are severely limited by the maximum duty factor attainable with SLAC type S-band klystrons. This long duty factor is required because of the limited instantaneous currents which can be accelerated in SLAC type structures without beam breakup. If the current limit can be increased by a factor of two, use of existing klystron designs at moderate cost will be possible. A design study to optimize the current SLAC s-band cavity structure for a 2-GeV design is underway. Detailed calculations of beam dynamics, possible focusing systems, and resulting current thresholds for beam breakup are being carried out.

b. Design Study, Bicyclotron

Recently a new magnet configuration called the "bicyclotron" has been proposed to avoid the massive and expensive return magnets which characterize the usual microtron design for 1—2-GeV electron accelerators. The bicyclotron system is characterized by strong vertical defocusing forces generated by the large slant angle at which the beam enters and leaves the segment magnets. We are studying possible schemes for compensating for these defocusing forces, by computer analysis of various configurations of segment magnets and quadrupole focusing elements. Possible more complex field variations in the segment magnets are also studied, as well as detailed predictions of beam size and emittance.

c. Microtron Beam Blowup

One of the unknown limits on performance of c.w. 1—2 GeV electron microtrons is imposed by the onset of cumulative beam blowup generated during multiturn passage through an rf accelerating cavity. Preliminary calculations for simple conceptual designs have suggested that the threshold for such blowup is circulating currents in the low 100 μamp range. No experimental verification has been possible to date. The threshold will be a sensitive function of the configuration of focusing elements in the orbit geometry. We are studying by orbit analysis the expected properties of beams in the 1—2 GeV for several possible configurations of magnet and focusing elements. The particular objective is to establish limits expected due to beam blowup.

d. Transient Response of Standing-Wave rf Structures

To date conceptual designs of linac-stretcher ring systems for obtaining 2-GeV c.w. beams have employed only conventional SLAC type disk-loaded wave guides. However, because of their much higher shunt impedance, standing wave accelerating structures functioning in a pulsed mode as injectors into a stretcher ring may result in a more efficient c.w. accelerator. Preliminary estimates indicate substantial savings in capital and operating cost are possible. The major uncertainty in their performance is their transient response to an injected electron beam and the attendant energy spread. Calculations of transient response of somewhat idealized systems are in progress, and possibilities of measurements on prototype systems in collaboration with CRNL-LASL scientists are under discussion.

Microtron Development

During the remainder of 1980, efforts will concentrate on the design and fabrication of a prototype of the segment magnet for a 2-GeV double-sided microtron. Because of the character of the magnet, the project can naturally proceed in two successive phases. The first will consist of design, fabrication, and field measurements of that portion of the magnet containing orbits in the range 30—300 MeV. During this period an engineering and design study will determine fabrication costs for both the partial and full magnets. Assembly of the partial magnet will begin. It is anticipated that this phase of the magnet study will require ∿9 months.

Testing of the partial prototype magnet will be completed during 1981. Field measurements will be made with a precision of ±0.1% and spatial resolution of ±0.5 mm. The results will be compared with the assumptions used in the preliminary bicyclotron design study. Pending confirmation of orbit stability, a complete prototype will then be constructed. During this period, we will also continue to examine the technical and scientific requirements for all aspects of a 2-GeV accelerator facility.

By 1982 a critical decision point is anticipated on the optimum design for a 2-GeV electron accelerator. Magnet studies at ANL will have been completed. Studies of possible rf accelerating structures at LASL will have reached a definitive stage and limits on electron beam breakup thresholds will have been established in the 170-MeV microtron system under construction at the National Bureau of Standards. We plan to develop a detailed microtron design with complete cost and time schedule in 1982.

EXPERIMENTAL ATOMIC AND MOLECULAR PHYSICS RESEARCH

INTRODUCTION

The Atomic Physics research in the Physics Division consists of five ongoing experimental programs as follows:

A. Dissociation and Other Interactions of Energetic Molecular Ions in Solid and Gaseous Targets (D. S. Gemmell)

B. Beam-Foil Research and Collision Dynamics of Heavy Ions (H. G. Berry)

C. Photoionization-Photoelectron Research (J. Berkowitz)

D. Spectroscopy of Free Atoms and Molecules: High Precision Laser-rf Double-Resonance Spectroscopy with Atomic and Molecular Beams (W. J. Childs, L. S. Goodman, S. A. Lee)

E. Mössbauer Effect Research (G. J. Perlow)

IX. EXPERIMENTAL ATOMIC AND MOLECULAR PHYSICS

A. DISSOCIATION AND OTHER INTERACTIONS OF ENERGETIC MOLECULAR IONS IN SOLID AND GASEOUS TARGETS

Electrostatic accelerators can produce a rich spectrum of molecular-ion species (see, for example, Fig. IX-1). At the 4-MV Dynamitron in the Physics Division, tightly collimated beams of molecular ions with energies variable in the range 0.5—4.0 MeV are directed onto thin (∿100-Å) foil or gas targets. The distributions in energy and angle are measured with high resolution (∿0.005° and ∿300 eV) for the resultant collisionally-induced dissociation fragments. The two major aims of the work are (a) a general study of the interactions of fast ions with matter, but with emphasis on those aspects unique to the use of molecular-ion projectiles and (b) a study of the structures of the incident molecular ions. These two aspects of the work are mutually interdependent. In order to derive structure information about a given molecular ion, one needs to know details about the way the dissociation fragments collectively interact with the target in which the dissociation occurs. Similarly, a knowledge of the structure of the incident molecular ions is important in understanding the physics of their interactions with the target. We have therefore begun our work with careful studies involving beams of the simplest and relatively well understood diatomic molecular ions (H_2^+, HeH^+, etc.). Even with these, several new and interesting phenomena have been encountered (e.g., the interactions between the molecular constituents and the polarization oscillations that they induce in a solid target, the marked differences in dissociations induced in gases as compared with those in foils, the anomalously high transmission of some molecular ions through foils and the apparent absence of any transmission in other cases). As our understanding of these phenomena develops, we plan to go on to studies involving more complex projectiles.

In 1979 we completed extensive modifications (begun in 1978) to our beam line at the Dynamitron accelerator. These modifications now permit measurements in which two or more fragments from a dissociating molecular projectile can be detected in coincidence. In addition to measuring the energies and directions of emission of these fragments, we also obtain precise information on their charge states and their times of flight from the target. This type of measurement greatly improves the accuracy with which the stereochemical structures of fast molecular projectiles can be determined. During 1979 we have calibrated the apparatus using a 3.6-MeV Kr^+ beam and have successfully tested it with coincidence measurements on simple diatomic projectiles. A start has also been made on structure determinations for some triatomic species (H_3^+, CH_2^+, NH_2^+, OH_2^+).

The year 1979 also saw the first measurements in a collaborative experiment involving Argonne National Laboratory and the Universities of Bonn and Cologne. This work uses a 28-MeV H_2^+ beam from the University of Bonn cyclotron to study polarization wake forces extending over several plasma oscillation periods.

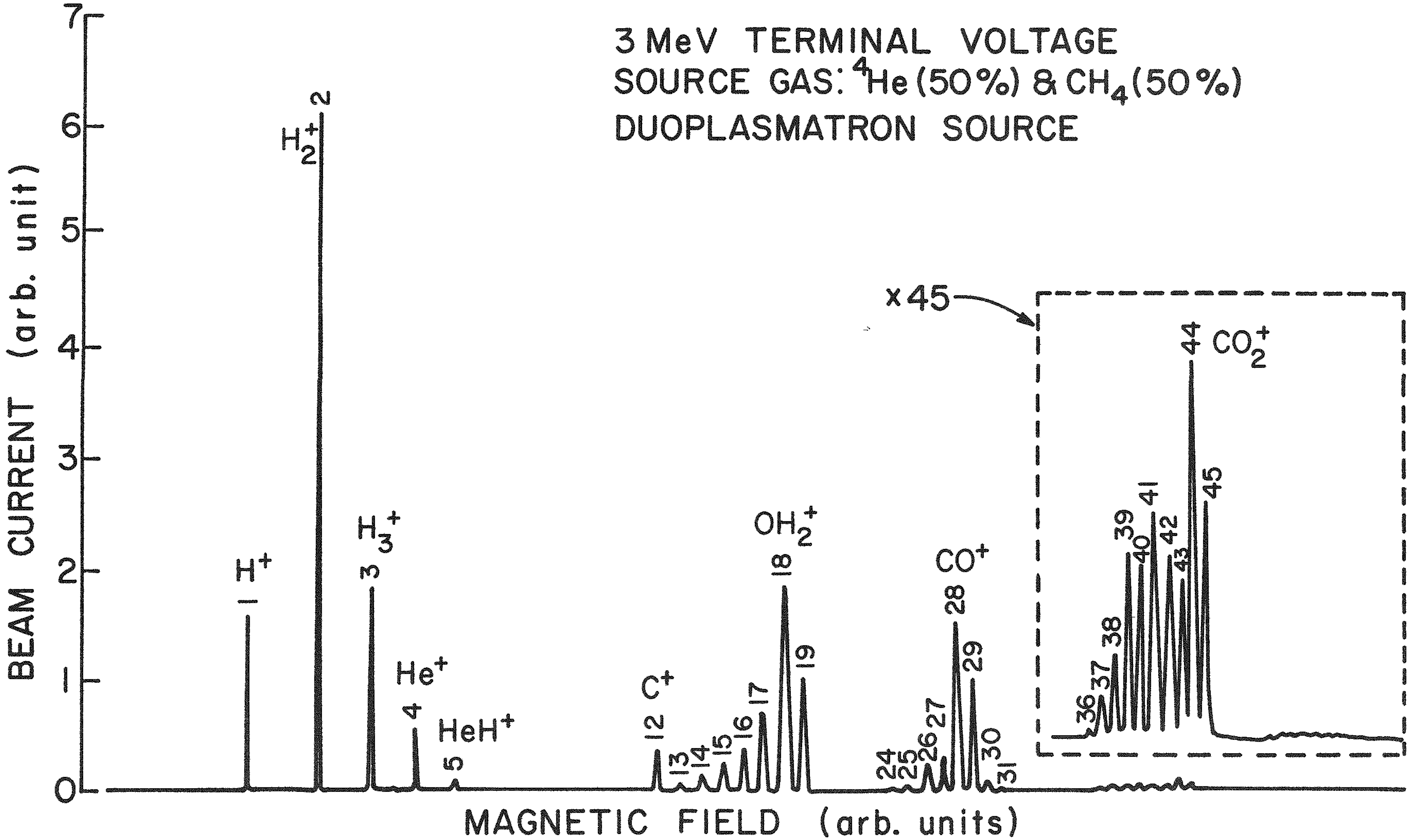

Fig. IX-1. A "mass scan" of the ion beams emerging from the Physics Division's 4-MV Dynamitron accelerator operating with a duoplasmatron ion source fed with a mixture of He and CH_4 gases.

Recent measurements at the Dynamitron together with computer calculations have given rise to a quantitative understanding of the "transmission" of H_2^+ ions through foils. Work with N_2^+ and N^+ beams has led to the discovery of new phenomena seen in the charge-state dependence of multiple-scattering distributions.

On August 20-21, 1979 Argonne hosted an informal workshop on "Physics with Fast Molecular-Ion Beams."

a. Modifications to the Apparatus

D. S. Gemmell, P. J. Cooney, E. P. Kanter, and B. J. Zabransky

To permit coincidence experiments, extensive modifications have been made to the beam-line downstream from the target chamber. Ion fragments emerging from the target now enter a 20-in. diameter magnetically shielded stainless-steel flight tube followed by a 20-in. gate valve and a vacuum manifold that houses two movable and tightly collimated detectors. Our electrostatic analyzer is coupled to the rear of this chamber. The two movable detectors are remotely controlled via a microcomputer slaved to the on-line PDP-11/45 data-acquisition computer and can be positioned to an accuracy of about 0.001 in. anywhere on a 20-in. diam. circular area that subtends an angle of 100 mrad at the target position. A commercial color TV has been interfaced (also via a microcomputer) to the PDP-11/45 to permit a graphics display of the relative positions of the detectors and of the various ion fragments emerging from the target.

In January 1979 the entire apparatus was calibrated using a 3.6-MeV beam of Kr^+ ions. This was followed by successful tests with coincidence measurements using dissociating diatomic projectiles (H_2^+, HeH^+, OH^+, etc.). The apparatus performed with the expected angular and energy resolutions and with a time resolution (using Si surface-barrier detectors) of 1.3 nsec for 1.5-MeV protons and 6.3 nsec for 0.2-MeV protons.

b. Molecular-Ion Structure Determinations

D. S. Gemmell, P. J. Cooney, E. P. Kanter, and B. J. Zabransky

(i) Measurements on Single Dissociation Fragments

Following our previously reported measurements on the ions H_3^+, CO_2^+ and N_2O^+, we have studied the series of ionic projectiles CH_n^+ (n = 0—4). From the systematic trends of the foil-induced Coulomb explosion spectra (all obtained at the same projectile velocity—corresponding to 200 keV/nucleon) (see Fig. IX-2), we have obtained qualitative information on the structures of these species. In particular, the series displays a narrowing of the angular and energy widths obtained for the carbon ions as protons are symmetrically added thereby providing a focusing effect. Because of the Jahn-Teller distortion, these widths are dramatically increased in the case of CH_4^+ projectiles. We believe this to be the first experimental demonstration of the Jahn-Teller distortion of the methane ion.

As a further example of the technique we have made measurements on the C^{2+} fragments arising from 3.6-MeV $C_3H_3^+$ ions dissociating in a thin-foil target and have demonstrated that the carbons sit on the corners of an approximately equilateral triangle. That is, the beam consists of cyclopropenyl and not propargyl (linear in carbon) ions.

(ii) Coincidence Measurements

The structures of most polyatomic molecular-ion projectiles can be determined much more precisely if spatial and temporal coincidences can be recorded for two or more dissociation fragments from a given projectile. We are now able to measure double or triple coincidences and to record simultaneously precise information on angles of emission, fragment charge states, energies, and flight times from the target.

Some preliminary results have been obtained for the dihydride ions CH_2^+, NH_2^+, and OH_2^+ (of these only OH_2^+ has had its structure determined by traditional photon techniques). We have measured spatial scans of the proton-proton coincidence rate for the foil-induced dissociation of these ions. Various combinations of post-deflector and electrostatic analyzer voltage settings were chosen in order to study different subsets of the incident projectile orientations. The most extensive measurements were for 3.6-MeV OH_2^+, where we derived values of 110 ± 2° and 1.0 ± 0.04 Å for the O-H bond length and the H-O-H bond angle, respectively. These values agree with the values of 110.5° and 0.999 Å derived from optical measurements. We expect that a more detailed analysis, properly taking into account wake effects and multiple scattering, will result in a significant improvement in the level of accuracy.

Although foil-induced dissociation has the virtue that essentially every incident projectile dissociates violently into individual highly charged

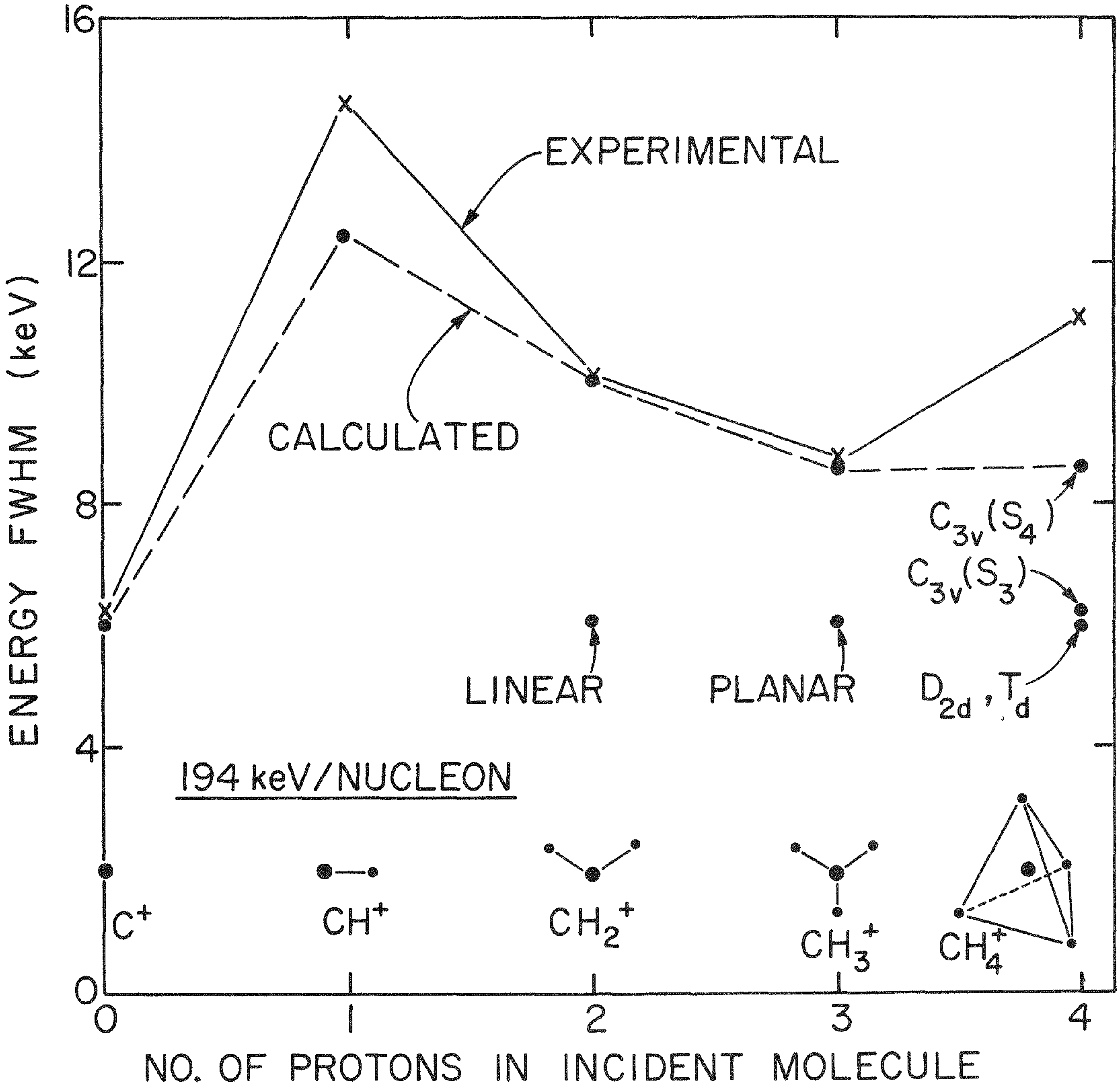

Fig. IX-2. Comparison of the energy widths measured at $\theta = 0$ for C^{4+} ions arising from the foil-induced dissociation of CH_n^+ ($n = 0, 4$). The (rough) calculations are based on effective charges of 3.5 for the carbon ions and 1 for the protons. The influence of the Jahn-Teller distortion of CH_4^+ is clearly seen.

monatomic ions, there are complications in the data analysis where one must take into account wake effects, target thickness, charge-state distributions, and multiple scattering. These problems do not arise if one uses a dilute gas target in which single collisions predominate. With gas targets, however, there is a problem in that most of the dissociations proceed through weak Coulomb explosions between ions having low charges. Also, the product fragments frequently include diatomic and polyatomic species. Thus the foil-induced and gas-induced dissociations tend to give complementary information and in the study of any given projectile, it is desirable to use both types of target.

We have begun triple coincidence measurements, e.g., on the pair of protons and the N^{3+} fragments arising from the dissociation of 3.6-MeV NH_2^+ ions in a dilute Ar gas jet. Although the triple coincidence counting rates are low, the data are very clean and the analysis is greatly simplified as compared with the results obtained with foil targets.

There are now several obvious refinements to be implemented (e.g., in the data analysis and in taking into account the time-of-flight information) that will permit considerably improved precision in the technique.

c. "Transmission" of Fast H_2^+ Ions Through Foils

D. S. Gemmell, P. J. Cooney, E. P. Kanter, I. Plesser, N. Cue,* J.-C. Poizat,† and J. Remillieux†

The small but definite fraction ($\sim 10^{-3}$ to 10^{-10}) of H_2^+ ions that emerge undissociated from a carbon foil bombarded with an H_2^+ beam has been studied further. We have shown in a 2-foil experiment that 1-MeV H_2^+ ions transmitted through a 330-Å carbon foil have a significantly larger average internuclear separation than do the initial projectiles. This was demonstrated by measuring the Coulomb explosion of the transmitted H_2^+ when they dissociated in a second foil downstream from the first.

We have developed a model for the transmission of H_2^+ that quantitatively reproduces both the transmitted fraction (as a function of velocity and foil thickness) and the distribution of internuclear separations in the transmitted ions. The model assumes stripping of the electron from H_2^+ upon entrance to the foil, followed by a Coulomb explosion and then electron capture

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at the foil exit. Multiple scattering in the foil plays a central role in this process.

d. Coulomb Explosion of N_2^+

D. S. Gemmell, I. Plesser, and B. J. Zabransky.

We have measured joint energy and angle distributions for nitrogen ions emerging from the foil-induced dissociation of 2-MeV and 3-MeV N_2^+ beams. The corresponding "ring patterns" display pronounced variations in shape for different emerging nitrogen ionic charge states. We are currently attempting to account theoretically for these variations. The N_2^+ projectile was chosen for study as a fairly simple example of a molecular ion containing two "heavy" atoms. An understanding of such projectiles is necessary in order to extend our molecular-ion structure studies to more complex species containing two or more heavy atoms ($C_2H_3^+$, HNO^+, etc.).

Experiments were performed measuring coincidences between N^{2+} and N^{n+} ($n = 0$—4) to see if there exists any dependence of the charge-state correlation upon the orientation of the incident 3-MeV N_2^+ ions. None was found. If this absence of an orientation dependence of charge-state correlations turns out to be true in general, it will greatly simplify the determination of structures of molecular ions by Coulomb-explosion techniques.

e. Charge-State Dependence of Multiple Scattering

D. S. Gemmell, P. J. Cooney, E. P. Kanter, I. Plesser, and B. J. Zabransky

To understand the foil-induced Coulomb explosion of N_2^+ and other molecular ions containing heavy atoms, it is essential to have detailed knowledge about the multiple scattering, stopping power, charge-state distributions, etc. of the corresponding monatomic fragments. We have therefore begun such measurements with the monatomic projectiles C^+, N^+, O^+ and Ne^+ and have determined the dependences of the multiple-scattering distributions and energy losses upon such factors as beam velocity, exiting ionic charge state, foil type and foil thickness. We have discovered a striking and not previously reported dependence of the width of the multiple scattering distribution upon the exiting ionic charge state. For the highest charge states this width can be as much as a factor of 5 larger than it is for the most probable charge states. We are developing a promising model for this phenomenon in terms of the production of ions with K-shell vacancies created in hard collisions with foil atoms.

f. Anomalous Alpha-Particle Backscattering

D. S. Gemmell, P. J. Cooney, E. P. Kanter, P. P. Pronko,* and B. J. Zabransky

A group at ORNL recently reported the anomalously high yield of 1-MeV α particles backscattered at ∿180° from several metal targets. We sought to verify this effect using the high angular resolution of our apparatus and a magnetic field to allow us to examine the backscattering at exactly 180°. No effect was found although there were some fluctuations in yield that were demonstrably due to planar channeling in microcrystals in the targets.

g. Probing the "Wake" of a Swift Ion in Matter

D. S. Gemmell, G. Krösing,† G. Kumbartzki,† and W. J. Pietsch‡

The polarization "wake" of a swift ion in matter was studied in a 2-foil experiment using the University of Bonn cyclotron. A thin carbon foil was used as a stripper for a 28-MeV H_2^+ beam. This served to initiate a Coulomb explosion between the two protons in each H_2^+ projectile. After a variable flight path (∿10 to 100 microns) which determined the separation of the two protons, they entered an Al foil where the wake interaction took place. This interaction was investigated via the 0° proton momentum spectrum observed downstream using a magnetic spectrograph. The results confirm (for the first time) the existence of a wake-force interaction over large distances (several hundred angstroms).

h. Workshop on "Physics with Fast Molecular-Ion Beams"

organized by D. S. Gemmell, P. J. Cooney, E. P. Kanter, and B. J. Zabransky

This informal workshop took place in the Argonne Physics Division on August 20-21, 1979. There were 35 attendees from 9 different countries.

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*Materials Science Division, ANL.

†University of Bonn, Bonn, Germany.

‡University of Cologne, Cologne, Germany.

The workshop focused on current work on such topics as molecular-ion dissociation and transmission, "wake" effects, ion charge states, cluster stopping powers, beam-foil spectroscopy and electron-emission studies with molecular-ion beams, molecular-ion structure determinations, etc.

A Proceedings (ANL/PHY-79-3) was published in October 1979.

B. BEAM-FOIL RESEARCH AND COLLISION DYNAMICS OF HEAVY IONS

Our present fast ion-beam atomic physics program consists of four major parts, two of which are investigations in atomic structure, and two of which involve collision physics. Part (1) involves work mainly at the Argonne Tandem accelerator, Parts (2) and (3) involve the Argonne Dynamitron accelerator, while Part (4) involves two small accelerators at the Accelerator Research Facilities Division.

(1) Atomic Structure of Highly Stripped Few-Electron Ions. This work provides tests of ab initio relativistic and quantum electrodynamic calculations. We have recently completed initial measurements of the $2s\,^3S — 2p\,^3P$ transitions of helium-like Si, S and Cl in a collaboration with A. E. Livingston at the University of Notre Dame. These results provide the most accurate tests of QED for these Z ions. We have developed a position-sensitive detector technique to multiplex the observed spectra, which provides an improvement in data collection time of 10 to 100.

Our 1/Z expansion calculations of the 2s-2p transition energy in the LiI-like sequence have provided accurate comparisons with experiment up to Z = 28, and suggest that many-electron effects on the one-electron QED corrections are below the 0.3% level.

(2) Atomic Structure of Heavy Ions. Further identifications in the KrVIII spectrum have been made, mainly between high angular momentum levels. These results improve our previous core polarizability estimates and should give a more accurate value of the ionization potential.

Identification work on the spectrum of KrVII has begun. The homologous spectra of 6 and 7 times ionized Ne and Ar are being studied in parallel. Better understanding, particularly of the yrast transitions, of these spectra is providing internal calibration lines in beam-foil spectra.

(3) Foil Interaction with Fast Ions. We have completed our study of the beam-energy dependence of the alignment of several neutral helium states. This work, together with our study of the temperature dependence of the alignment, and effects of neighboring nuclei on the atom emerging from the foil, is helping us to develop a model of the final surface interaction in terms of the secondary electron flux and the dipole interaction between the solid and the moving ion. An ultrahigh vacuum chamber with in situ foil evaporation has been constructed and will be used to study material dependences.

(4) Ion-Ion Charge Exchange Cross Sections. Low-energy symmetric charge changing collisions have recently become relevant to the inertial fusion program; such cross sections determine the limit of storage times and beam-transport properties of GeV energy ions used to impinge on the fusion producing pellet. Theoretical work on these cross sections at low energies (less than 10 keV/nucleon) is in a primitive stage: cross sections are determined from molecular level crossings which define the radius of interaction and hence do not predict the energy dependence. Our experiment involves a double accelerator design with two charged ion beams intersecting

at 90° with center-of-mass energies of 30 to 150 keV. Electrostatic analysis after the collision beam allows us to determine the charge states of the interaction products.

a. Excitation of Hydrogen by a Thin Carbon Foil

R. L. Brooks, H. G. Berry, T. J. Gay,* and R. DeSerio*

Continuing our observations of coherence of opposite parity states (e.g., 2s — 2p states) produced in thin foil excitation of hydrogen (thesis work of G. Gabrielse, 1979), we have observed its variation for molecular ion (H_2^+ and H_3^+) impact. The coherence disappears when a neighboring proton is within a few atomic diameters at the exit foil surface. These results help to set a distance estimate on the foil-hydrogen interaction. The mixing of the 2s and 2p states occurs for quite large internuclear separations up to 50 a.u. for both H_2^+ and H_3^+ initial projectiles.

b. Temperature Dependence of Alignment Production by Beam-Foil Impact

T. J. Gay* and H. G. Berry

We have completed our detailed observations of the foil temperature variations of the alignment of the HeI $3p\,^1P$ state produced in carbon foil excitation. We believe the effect is predominantly due to changes in the secondary electron fluxes which we have verified vary strongly with foil temperature. The alignment variation is found to be a general effect for all helium excited states. The temperature dependence of the alignment is found to modulate as a function of the projectile velocity for the $3p\,^1P$ state, but modulations are observed for other HeI states ($3p\,^3P$, $3d\,^{1,3}D$).

This work constitutes part of T. J. Gay's Ph.D. thesis.

c. Energy Dependence of Alignment Production

T. J. Gay* and H. G. Berry

We have measured the beam-energy dependence of the alignment production of the four HeI excited states, $3\,^{1,3}P$, $3\,^{1,3}D$, using carbon foil excitation between 20 keV and 1 MeV. The results test some preliminary stark effect theoretical models of the beam-foil interaction. We show that the velocity dependences of the alignments observed for the above 4 states do not agree

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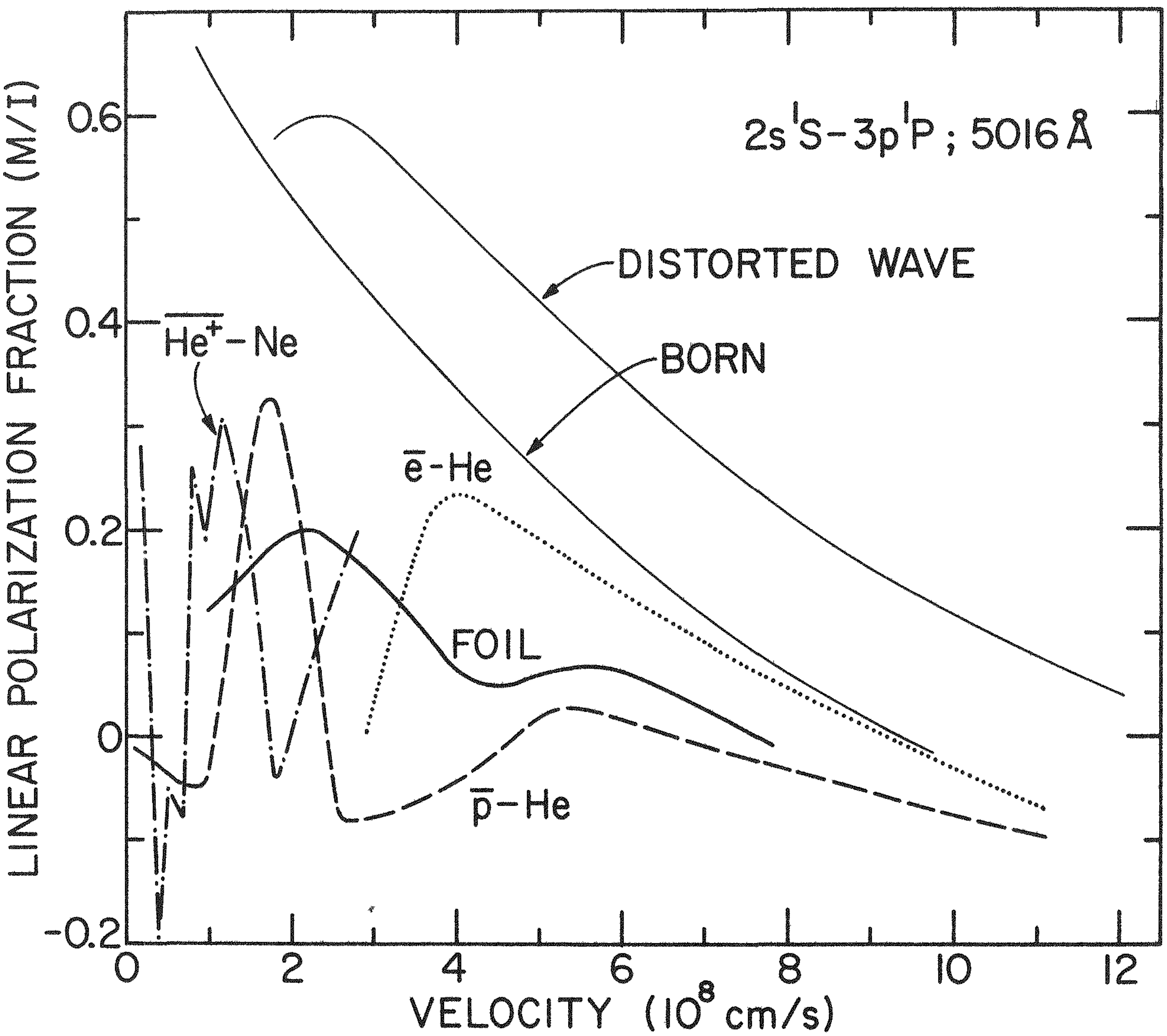

Fig. IX-3. Comparison of 5016 Å polarization in HeI excited by a thin carbon foil (thick solid line) with theory (distorted wave and Born) and other experiments—e-He (dotted), He^+-Ne (dash-dot) and p-He (dashed).

with stark effect mixing of the n = 3 levels by a final surface electric field. More significant comparisons have been made with alignment production observed fast ion-atom collisions. In Fig. IX-3 we compare the 5016 Å polarization with theory (Born and distorted wave) and with other collisions. This work has involved collaborations with R. M. Schectman at the University of Toledo and R. Hight and D. Burns at the University of Nebraska.

d. Molecular Effects in the Light Yields of Beam-Foil Collisions

T. J. Gay* and H. G. Berry

As for hydrogen (1), we find strong molecular effects in the light yield from HeI excited states after beam foil excitation using HeH^+ molecules. As well as large changes in the alignment, variations of factors up to 5 also occur in the total light yields from different excited states. A preliminary model of the effect has been suggested which incorporates the final state surface/ion interaction plus a longer range molecular interaction. The latter is sensitive to long-range level crossings and provides a possibility to study very low-energy ion-ion interactions. In an initial publication[1] we have proposed a final surface de-excitation mechanism which is reduced in the presence of a neighboring projectile ion. In Fig. IX-4 the variations of light yield with final surface internuclear separation, we show their sensitivity to the final atomic state, probably due to long-range molecular level crossings in the HeH^+ molecular ion.

This work constitutes part of T. J. Gay's Ph.D. thesis.

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*Thesis student, University of Chicago, Chicago, Illinois.
[1]T. J. Gay and H. G. Berry, J. Phys. B 13, L199 (1980).

e. Lamb Shift and Fine Structure of n = 2 in Helium-like Chlorine, Sulfur, and Silicon

R. DeSerio,* H. G. Berry, R. L. Brooks, A. E. Livingston,† J. A. Poirier,† and S. Hinterlong†

We have measured the wavelengths of the $2s\,^3S$—$2p\,^3P$ transitions in ClXVI, SXV, and SiXIII at the Notre Dame tandem facility. The preliminary results show good agreement with our earlier ClXVI work, and future high

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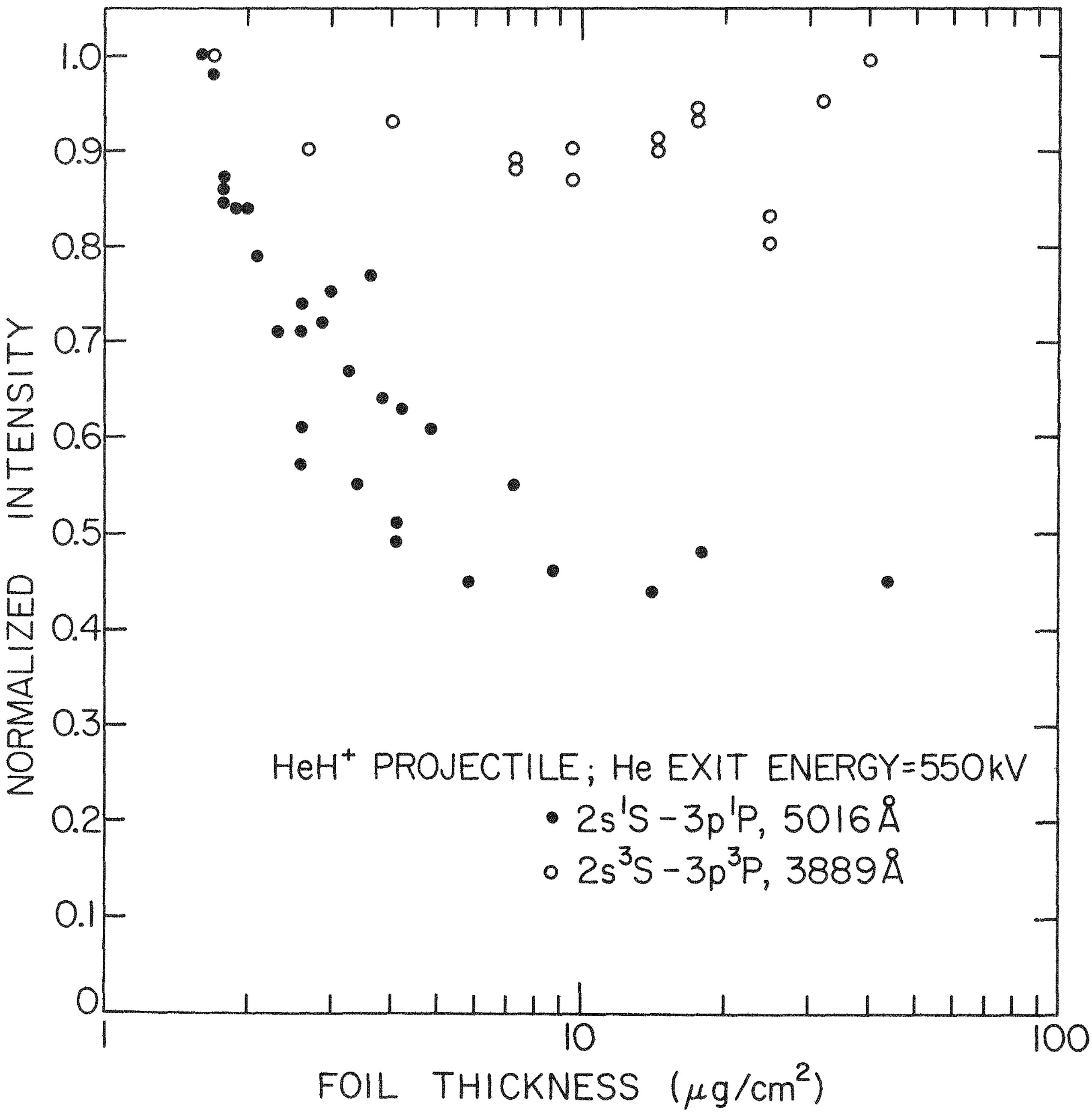

Fig. IX-4. Variation of light yield for different thickness foils using HeH^+ projectiles.

TABLE IX-I. Energies (in cm^{-1}) of $2s\,^3S$—$2p\,^3P$ transitions in helium-like silicon, sulfur, and chlorine.

	$^3S_1 - {}^3P_2$			$^3S_1 - {}^3P_0$		
Z	Experiment	Theory	QED	Experiment	Theory	QED
14	122745(15)[a] 122775(60)[b]	122721	-499	113790(25)[a] 113856(90)[b]	113771	-530
16	148480(20)[a]	148470	-794	132200(40)[a]	132169	-846
17	162920(25)[a] 162913(6)[c]	162893	-979	141672(13)[c]	141558	-1045

[a]Our work at the Notre Dame Tandem.

[b]Silver et al. at the Oxford Tandem.

[c]Our work at the Argonne Tandem.

precision work is expected to greatly improve our results. The measurements already test relativistic theory and quantum electrodynamics at the 1% level of the Lamb shift. Our results are shown in Table IX-I, compared with our own Z expansion calculations, the QED calculations summarized by Mohr, and one other recent experiment on Si at the Oxford University Tandem accelerator.

This work constitutes part of R. DeSerio's and S. Hinterlong's Ph.D. theses.

f. Spectroscopy of Few-Electron Ions

H. G. Berry, R. DeSerio,* R. L. Brooks, and K. T. Cheng†

We have calculated the energy of the resonance 2s—2p transition of lithium-like ions using two ab initio techniques and compared with experimental results for Z = 3—28. We conclude that many-electron effects on the one-electron quantum-electrodynamic corrections are negligible to present

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†Radiological and Environmental Research Division, ANL.

experimental accuracy. Extensions of the theory to all first row atoms (up to 9 electrons) are being considered.

This work constitutes part of R. DeSerio's Ph.D. thesis.

g. Yrast Transitions in Highly Stripped Ions

R. L. Brooks, H. G. Berry, R. DeSerio,* and L. J. Curtis†

An outgrowth of our work both on KrVIII [Sec. VIII.B.g of last year's Annual Review (ANL-79-40)] and on two-electron chlorine is our present investigation of high angular momentum transitions between highly excited n states. Many of these transitions occur in the beam-foil excited spectra, and can be used as calibration lines for almost all such spectra. For simple closed cores, our observations fit a simple polarization theory, but other systems with open cores do not. We have made observations on homologous systems of Ne, Ar and Kr at Dynamitron beam energies. The analysis also leads to accurate ionization potentials of the ions observed.

h. Charge-Changing Cross Sections of Xe^+ on Xe^+

H. G. Berry, R. L. Brooks, J. Hardis,* and M. Mazarakis‡

A double accelerator system providing 20—100-keV singly-charged ions from each source has been built. Both systems incorporate magnetic quadrupole focusing and magnetic dipole momentum analysis to provide Xe^+ ion beams on target at ultrahigh vacuum of 10^{-9} torr. Upgrading of the beam geometry is in progress. Beams were produced on target in November 1979, but present beam densities are too low. A charge analysis system after one beam allows us to measure Xe^0, Xe^{1+}, and Xe^{2+} fractions, and thus obtain the total charge exchange and ionization cross sections for Xe^+ on Xe^+. This program should be completed in 1980.

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C. PHOTOIONIZATION-PHOTOELECTRON RESEARCH

Our photoionization research program is aimed at understanding the basic processes of interaction of light with molecules, the electronic structures of molecules and molecular ions, and the reactions of molecular ions, both unimolecular and bimolecular. The processes and species we study are implicated in a wide range of chemical reactions, and are of special importance in outer planetary atmospheres and in interstellar clouds. Our work also provides fruitful tests for theories of electronic structure, which help in the evaluation of widely applicable models for multielectron systems. Most of this work is of a fundamental nature, but we also use the precise methods developed here to determine thermochemical quantities (heats of formation and ionization potentials) directly relevant in, e.g., reactions with ozone in the stratosphere and possible side reactions in a magneto-hydrodynamic generator. Our experimental studies utilize five pieces of apparatus—two photoionization mass spectrometers and three photoelectron energy analyzers—each with special features.

(1) A three-meter normal-incidence vacuum-ultraviolet monochromator combined with a quadrupole mass spectrometer. This apparatus is capable of the highest resolution currently achieved in photoionization studies. It is also convenient for investigations of wavelength-dependent photoelectron spectra.

(2) A one-meter normal-incidence VUV monochromator mated with a magnetic-sector mass spectrometer. This apparatus has higher mass resolution, is less discriminatory in relative ion-yield measurements, and can be used to study metastable ions. Higher intensity for weak signals can also be achieved.

(3) Two cylindrical-mirror photoelectron-energy analyzers, which accept a large solid angle of photoelectrons, close to the "magic angle" of 54°44'. One has been extensively used for the determination of the photo-electron spectra of high-temperature species in molecular beams, and the other has recently been mated with the three-meter monochromator for studies of photoelectron spectra as a function of wavelength.

(4) A hemispherical electron-energy analyzer incorporated in a chamber which permits one to rotate the analyzer over a substantial fraction of 4π. This device is intended for angular-distribution measurements, and also enables us to study very-high-temperature species.

An ArF excimer laser has recently been acquired, and will soon be used in studies of multiphoton ionization and as a tool for the preparation of short-lived intermediates.

The measurement of photoelectron spectra of involatile materials has concentrated this year on higher temperature vapors. A double-oven apparatus has enabled us to sort out the photoelectron spectra of lithium halide monomers and dimers. The vapors of AgCl, AgBr, and AgI were investigated, and clear spectra of the diatomic species were obtained. Calculations by the X_α-DVM technique provided a very satisfactory interpretation, distinguishing the valence halogen and inner Ag 4d-like orbitals. Comparisons were made with CuCl, which has been found to exhibit unusual conductivity properties.

The vapor above AgI produced a substantial fraction of atomic iodine. The relative intensities of the fine structure components of I^+ produced by photoionization were quantitatively described by an irreducible tensor angular momentum coupling scheme, which also rationalized earlier data on atomic chlorine and bromine. We consider this a breakthrough in the understanding of partial cross sections in the ionization of open-shell atoms. Further experimental work is underway on other open-shell configurations.

The high-temperature oven has subsequently been used for variable wavelength photoionization mass spectrometry. Lithium chloride vapors were analyzed. The ionization potentials of LiCl and Li_2Cl_2 determined by photoelectron spectroscopy were confirmed, and a value for Li_3Cl_3 was obtained. The sequence of ionization energies of alkali halide clusters was examined by X_α-DVM calculations, and by a variety of ionic model calculations. A better understanding of the structures and stabilities of M_2X^+, $M_2X_2^+$, $M_3X_2^+$, $M_3X_3^+$, and $M_4X_4^+$ was thereby obtained, as well as for neutral MX, M_2X_2, M_3X_3, and M_4X_4.

More recently, we have obtained variable wavelength spectra of atomic iodine and atomic tellurium. These spectra are quite complicated, with autoionization structures from many Rydberg series.

Variable wavelength photoelectron spectra were obtained on O_2, N_2O, and CS_2, using a 3-meter monochromator and cylindrical mirror analyzer.

A search was conducted for doubly-ionized species produced by photoionization at 584 Å and 304 Å in a large range of molecular compounds, using a time-of-flight mass spectrometer.

a. Photoelectron Spectroscopy of Lithium Halide Monomers and Dimers

J. Berkowitz, C. H. Batson, and G. L. Goodman

The He (I) photoelectron spectra of "pure" monomers and dimers of the lithium halides have been obtained by using a double-oven technique to vary the dimer:monomer ratio. A representative set of spectra for lithium iodide is shown in Fig. IX-5. The lithium halide monomer spectra conform nicely to a model based on spin-orbit and ligand field interactions previously introduced. The first ionization potentials of the dimers are in each case higher than in the corresponding monomers. These conclusions are also deduced in this paper by ionic model calculations and molecular calculations of the X_α type, using the discrete variational method. The X_α calculations enable us to assign tentatively the dimer valence bands. These calculations have been extended to trimer and tetramer structures and indicate an oscillation in the first ionization potential in the series encompassing monomer

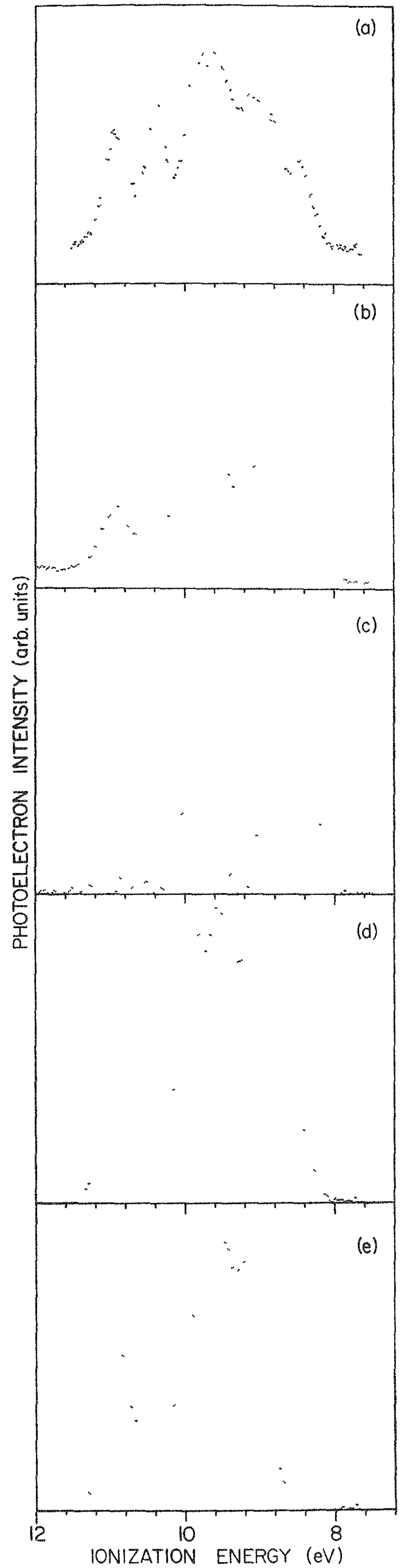

Fig. IX-5. (a) He (I) photoelectron spectrum of LiI without superheating, T ≅ 800°K. (b) He (I) photoelectron spectrum of LiI with superheating, T ≅ 800°K. (c) Pure monomer LiI spectrum, obtained by subtracting (a) from (b), after background subtraction and normalization at dimer band. (d) A spectrum with 50% of the monomer subtracted, to demonstrate the effect of reduction on the various peaks. (e) Pure dimer (Li_2I_2) spectrum, obtained by subtracting (c) from (a), after normalization at monomer band.

through tetramer. Some experimental verification exists up to trimer. The oscillatory behavior is also obtained in a crude ionic model calculation. An experimental method using photoionization mass spectrometry is suggested for the study of large clusters and is tested for Na_2I_2.

b. Partial Cross Sections in the Photoionization of Open-Shell Atoms

J. Berkowitz and G. L. Goodman

Both the photoelectron spectra (partial cross sections) and the photoionization spectra including resonances now seem to be well understood for closed shell systems. The recent application of the relativistic random phase approximation (RRPA) to the noble gases provides a particularly satisfying agreement between theory and experiment. Open-shell atoms, which constitute the bulk of the periodic table, are much more difficult, both experimentally and theoretically. Little experimental information exists, since these atomic species are much more difficult to generate. The attempts at theory thus far are inadequate.

We have recently obtained the He I photoelectron spectrum of atomic iodine from a thermal source (AgI), which generates a substantial abundance of atomic iodine in the ground ($^2P_{3/2}$) state. The sharp atomic iodine peaks can be readily seen above the broader structure due to AgI vapors in Fig. IX-6. The relative intensities of atomic iodine peaks were compared with recent data on Cl and Br. The major difference is an inversion in the relative intensities of $^3P_0$ and $^1S_0$ between Cl and I. An intermediate coupling angular momentum treatment, combined with spectroscopic mixing parameters, reproduces this inversion quantitatively, and, in addition, adequately describes the entire intensity pattern for all three halogens. A summary of experimental and calculated relative intensities is given in Table IX-II. The strong implication is that angular factors and mixing parameters are the dominant features in determining relative intensities, and radial integrals and "anisotropic electron-ion interactions" are much less important, over a small energy range.

We feel that this model should be a good starting point for ab initio calculations of partial cross sections and anisotropy parameters.

We have extended these calculations to several other open-shell cases, including p^4 and p^3 systems. We are currently trying to develop a source that will generate a p^4 atom to test this theory.

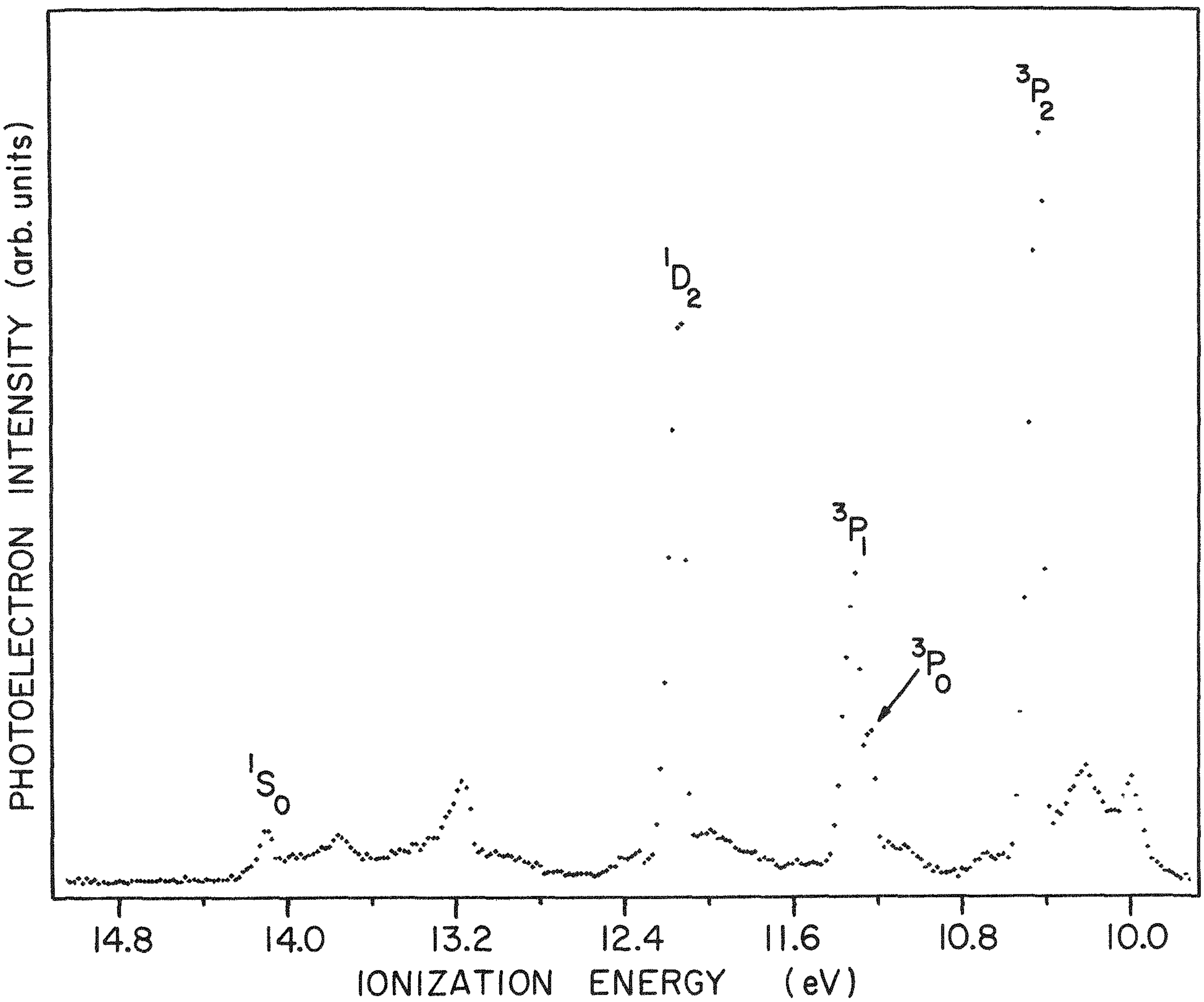

Fig. IX-6. He I photoelectron spectrum of atomic iodine, generated by vaporizing silver iodide at $\tau \sim 1000°K$. Background structure consists of various silver iodide and I_2 bands.

TABLE IX-II. Comparison of measured and calculated relative intensities of final states in the photoionization of halogen atoms.

	Cl		Br		I	
	Expt.[a]	Calc.[b]	Expt.[a]	Calc.[b]	Expt.[b]	Calc.[b]
$^3P_2$	0.540		0.563		0.566	
		0.565		0.604		0.636
$^3P_1$	0.238		0.287		0.190	
		0.200		0.200		0.200
$^3P_0$	0.032		0.034		0.095	
		0.048		0.067		0.097
$^1D_2$	0.437		0.399		0.447	
		0.435		0.395		0.364
$^1S_0$	0.086		0.051		0.035	
		0.086		0.066		0.037

[a]Data of K. Kimura, T. Yamazaki, and Y. Achiba, Chem. Phys. Lett. 58, 104 (1978).

[b]Present results.

c. Photoelectron Spectroscopy of AgCl, AgBr, and AgI Vapors

J. Berkowitz, C. H. Batson, and G. L. Goodman

He I photoelectron spectra of AgCl, AgBr, and AgI vapors have been obtained which differ significantly from earlier work. In each instance, the characteristic features of the diatomic molecule are prominent. The spectral features separate into a valence region, predominantly halogen p-like, and a deeper region, predominantly of Ag 4d character. The latter is split by spin-orbit and ligand field interactions, which are parameterized from the experimental data. Relativistic calculations of the X_α-DVM-SCC type have been performed for these species. At the transition state level, they agree very well with the experimental peak positions. Nonrelativistic calculations of this type have been performed for CuCl and cyclic Cu_3Cl_3. Unlike the AgX species, the CuCl and Cu_3Cl_3 exhibit strong mixing of metal d and halogen p orbitals for the uppermost occupied orbital, and other Cu 3d-like orbitals above the Cl 3p-like orbitals. It is suggested that the occurrence of Cu 3d orbitals in the valence region may play a role in the anomalous diamagnetic signal and large conductivity changes of CuCl condensed from the vapor.

d. Photoionization of Lithium Halide Vapors: The Structure and Stability of Alkali Halide Molecules and Ions

J. Berkowitz, G. L. Goodman, and C. H. Batson

The double-oven approach, combined with photoelectron spectroscopy (PES), enabled us to deduce the photoelectron spectra of lithium halide monomers and dimers. The dimers were found to have substantially higher (ca. 1 eV) first ionization potentials than the monomers. Extension of this research to higher clusters requires mass analysis. We have performed a photoionization mass spectrometric study of lithium chloride vapor, which contains ca. 5% trimer. This experiment confirms the earlier PES results on monomer and dimer, and yields a value for trimer which is very nearly the same as the dimer.

Quantum mechanical calculations on these larger clusters are sparse. A Hartree-Fock calculation on Li_nF_n predicts that trimer has a higher (ca. 0.45 eV) I.P. than dimer. Our own X_α calculations indicate a slightly lower I.P. for trimer than dimer, for both LiCl and LiF. Further work is necessary to achieve our ultimate goal of bridging the range from diatomic molecule to bulk microcrystal for this property.

In the course of this work we have examined 5 different ionic models in order to test their ability to predict energies of formation, ionization potentials and geometric structures for the neutral alkali halide clusters and their ions.

Although the more sophisticated of these (Brumer-Karplus and Rothberg models) predicted the stability and geometry of the neutral clusters adequately, they seemed to be much poorer for the ions. A particular point of focus is the structure of the triatomic ions M_2X^+. They are known experimentally to be highly stable, but their structures (bent or linear) are unknown. Some of the ionic models predict predominantly linear structure for this class of alkali halide ions, others predominantly bent. We are currently planning an experiment (in collaboration with D. S. Gemmell) to determine these geometries.

e. Photoionization of Open-Shell Atoms

J. Berkowitz, G. L. Goodman, and C. H. Batson

We had earlier (Sec. IX.C.b) described the need for more data on the photoionization of open-shell atoms. We have now used the vaporization of AgI as a source of atomic iodine and obtained a variable wavelength photoionization spectrum, at a resolution of 0.28 Å. Rydberg series were analyzed, and differed slightly in some convergence limits from those obtained by photographic absorption. The shapes of the resonances varied, the most prominent being d-like Rydberg series with profiles that indicated a relatively small q, indicating a large interaction between the Rydberg states and the continuum.

We have also found two thermal sources for atomic tellurium. The first provided satisfactory photoionization spectra from ionization threshold to ∿1070 Å. However, this source still had a large molecular (Te_2) component which prevented us from studying the region below 1070 Å because the process

$$Te_2 + h\nu \rightarrow Te^+ + Te + e$$

began to contribute at that energy.

The second source has a much lower molecular component, and has enabled us to extend this study to ∿670 Å. Autoionizing Rydberg series converging to $^2D_{3/2,5/2}$ and $^2P_{3/2}$ states of Te^+ are readily observed (corresponding to the excitation of a valence 5p electron) but no series is evident which would have $^2P_{1/2}$ as its convergence limit. In addition, we can observe the first few members of a series corresponding to the excitation of an electron from the inner 5s orbital.

This study is nearly complete. When combined with our existing high-resolution Xe spectrum, we can compare the photoionization behavior of the $5p^4$, $5p^5$, and $5p^6$ atomic systems. In this set, the radial wave functions should not differ greatly, and the major factor responsible for the increasing complexity should be the angular momentum coupling.

This study also has relevance to a scheme currently under investigation as a potential laser system for laser fusion. Some atoms of Group VI (O, S, Se, Te) when generated in the excited $^1S_0$ state by molecular photodissociation are expected to exhibit laser action. A possibly major loss mechanism is autoionization. A knowledge of the energy levels of the autoionizing states, and their strengths, should provide a useful test for theories attempting to model this process, even though the initial state for the present study is the $^3P_2$ ground state. Our success in developing an atomic Te source gives us some hope of obtaining the photoelectron spectrum of atomic tellurium, thereby enabling us to test the irreducible tensor analysis (see Sec. IX.C.b) on a p^4 configuration.

f. Fixed-Energy Photoelectron Spectroscopy

J. H. D. Eland

Two forms of molecular ultraviolet photoelectron spectroscopy are in current use: fixed wavelength photoelectron spectroscopy (PES) and threshold electron photoelectron spectroscopy (TPES). In PES light of fixed wavelength is used and the spectrum of ionic states is scanned using an electron energy analyzer to detect electrons of different energies. In TPES the electron energy accepted by the analyzer is fixed at zero, and the spectrum is scanned by varying the incident wavelength. Differences between photoelectron spectra and threshold photoelectron spectra of the same molecule arise because the threshold electron emission process proceeds not only through direct, vertical ionizing transitions, but also through autoionization from Rydberg states or shape resonances encountered as the wavelength is varied. In fixed wavelength PES, by contrast, choice of a short λ_{fix} normally ensures that vertical processes predominate, and the final ionic states can be clearly identified. In TPES many more states of the ions can be located, since they can be reached by nonvertical processes, but their relative intensities are hard to interpret, and they often form continua.

By scanning the exciting wavelength and accepting electrons of a fixed, nonzero energy, one can combine advantages of both techniques. A description of this technique has been accepted for publication in J. Chem. Phys.

g. Mass Spectra and Doubly Charged Ions in Photoionization at 30.4 nm and 58.4 nm

Bilin P. Tsai* and John H. D. Eland

Doubly charged ion abundances and photoionization mass spectra produced by He Iα and He IIα were measured for molecules from several classes of compounds. More doubly charged ions relative to singly charged ions are produced by photon impact than by electron impact at the same energy, the contrast being most marked for small polyatomic molecules. Lifetimes of doubly charged ions were measured for CO_2^{2+}, COS^{2+}, CS_2^{2+}, and DI^{2+}. It is concluded that at 30.4 nm initial double ionization is a substantial fraction of total ionization for all large molecules, and must appear in the photoelectron spectra.

h. Vibrational Level Populations in the Autoionization of Oxygen

J. H. D. Eland

Autoionization from the I and I' resonance series of O_2 has been reexamined using high resolution for photons and electrons. Photoelectron spectra on the resonances are predicted from the upper potential energy surface parameters and photoionization yield curve alone, without reference to the uncertain line shapes and widths. Bond lengths are determined as 1.370 ± 0.005 Å in I and 1.380 ± 0.005 in I' of O_2.

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*University of Minnesota, Minneapolis, Minnesota.

D. SPECTROSCOPY OF FREE ATOMS AND MOLECULES: HIGH-PRECISION LASER-rf DOUBLE-RESONANCE SPECTROSCOPY WITH ATOMIC AND MOLECULAR BEAMS

In the past year, the high precison and high sensitivity of the laser-rf double-resonance technique has been applied to make measurements of (a) the electric quadrupole moment of the exceedingly rare (0.09% abundant) isotope ^{138}La, (b) the hyperfine structure of a large number of metastable atomic states of Pr I, and (c) the rotational dependence of the spin-rotation and hyperfine interactions in CaF.

When the experimental and theoretical work on Pr is complete, we expect to achieve a systematic understanding of the hfs of all the low-lying levels of this atom in terms of a small number of radial parameters that can be compared directly with ab initio calculations.

The CaF measurements comprise the first systematic investigation in any molecule of the dependence of the spin-rotational and hyperfine interactions on the rotational quantum number N. This work opens up a new area of research that will include investigations of molecules of interest both to energy research scientists and to astrophysicists.

In addition to the measurements described below, some effort was put into upgrading our apparatus. The most notable improvement was the construction of an interferometric "lambda-meter" which measures the wavelength of our tunable laser to ±0.01 Å by comparison with a He-Ne standard using fringe-counting techniques. The λ meter was essential for the molecular work.

a. Measurement of the ^{138,139}La Nuclear Electric-Quadrupole Moment Ratio

W. J. Childs and L. S. Goodman

Although the NMR technique has been used to obtain a high-precision measurement of the 0.09% abundant ^{138}La nuclear magnetic-dipole moment by comparison with ^{139}La, only a rough value could be obtained for the electric-quadrupole moment ratio. In addition, the techniques of optical spectroscopy, including high-resolution tunable lasers, have not had sufficiently high resolution for this purpose because of the small size of the quadrupole effects. The laser-rf double-resonance technique was therefore used to measure two hfs intervals in the ^{138}La atomic ground term $5d6s^2\ ^2D_J$ to 1 ppm. From these measurements and previously known high-precision data on the hfs splittings of ^{139}La, it was possible to obtain the result[1,2]

[1] W. J. Childs and L. S. Goodman, Phys. Rev. A 20, 1922 (1979).

[2] L. S. Goodman and W. J. Childs, Symposium on Atomic Spectroscopy (SAS - 79), Tucson, Arizona, 10-14 September 1979, organized by J. O. Stoner, Jr. (University of Arizona, 1979), p. 166.

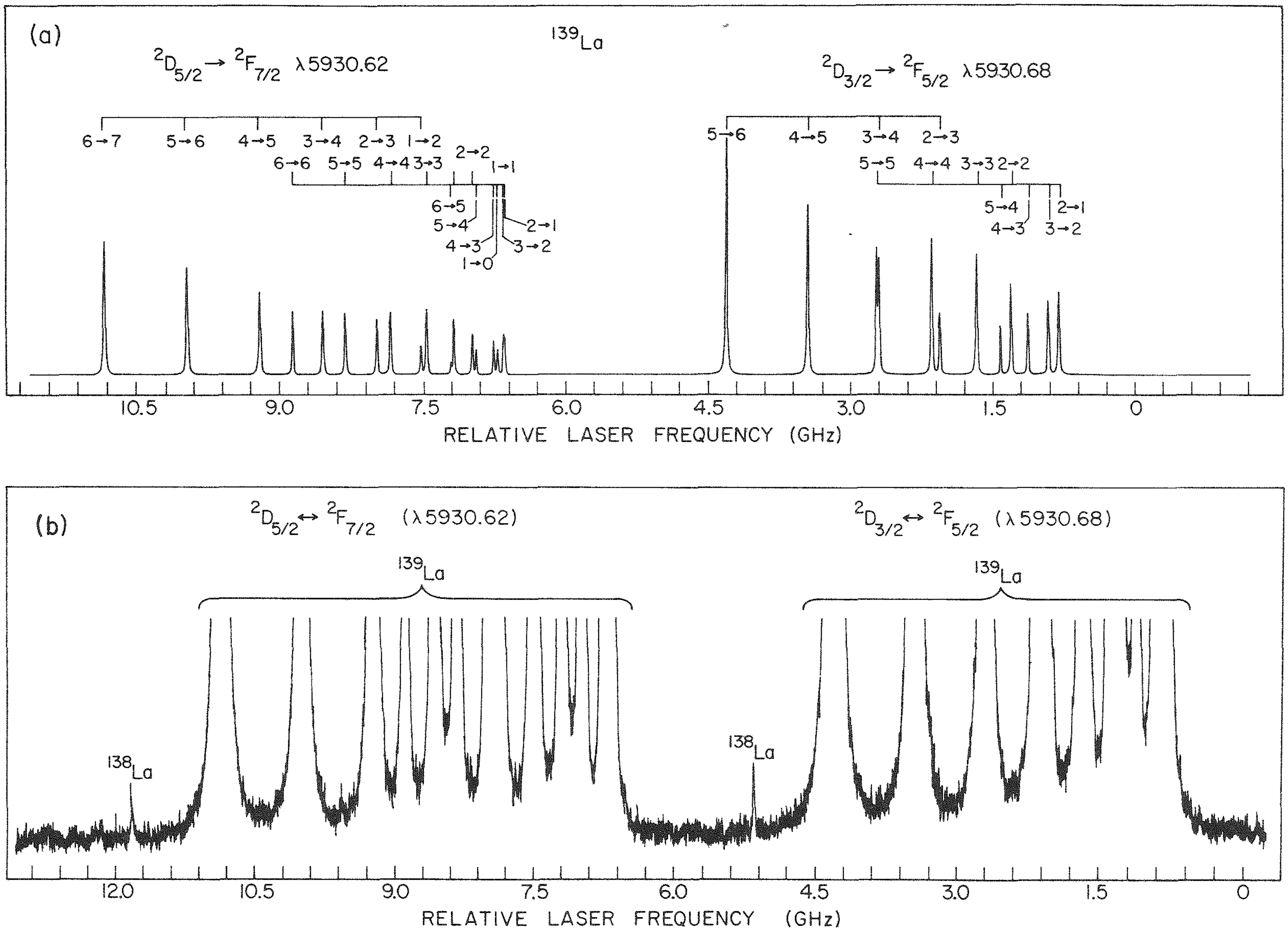

Fig. IX-7. (a) Laser fluorescence spectrum of the La I lines λ5930.62 and λ5930.68. All of the hfs components shown are understood quantitatively and arise from the 99.91% abundant ^{139}La, for which I = 7/2. (b) The same spectral region shown in (a), but with a much stronger atomic beam. Two weak peaks due to hfs in the 0.09% abundant, odd-odd isotope ^{138}La (I = 5) can be seen. The laser-rf double-resonance spectroscopy described was performed on these two peaks.

$$\frac{Q(^{138}La)}{Q(^{139}La)} = +2.27 \pm 0.04,$$

in which the uncertainty is not experimental but arises from lack of knowledge of a possible hyperfine anomaly. From the accepted value for $Q(^{139}La)$, we therefore obtain the result

$$Q(^{138}La) = +0.50 \pm 0.07 \times 10^{-24}\ cm^2$$

for this exceedingly rare, stable odd-odd isotope with I = 5.

The appearance of the very weak ^{138}La fluorescence signals used in making the double-resonance measurements can be seen in Fig. IX-7. The success of the experiment illustrates well the sensitivity of this powerful new technique.

b. Precision Measurement of hfs of Many Low Atomic Levels of Pr I

W. J. Childs, L. S. Goodman, and H. Crosswhite*

The purpose of this experiment is to achieve a systematic understanding of the hfs of all low-lying levels of a single atom in terms of a limited number of parameters, and then to compare their values with ab initio calculations. Praseodymium was selected primarily because of the very large number of excited levels that lie low enough to be populated in an atomic beam. High-precision results have so far been obtained for 17 levels of both parities. It is hoped that measurements can be made for an additional 10 or more levels, but this will depend on the accuracy of the existing classification of the extremely complex optical spectrum, and our work is casting serious doubt on some of this earlier work.

For the interpretation, iterative least-squares fits of the eigenvalues of the multiconfiguration energy matrices to the observed fine-structure levels have been carried out to obtain the necessary eigenvectors. Expectation values for the hfs constants of the levels of interest were then evaluated from these eigenvectors in terms of the appropriate hfs radial integrals. These were in turn varied as parameters to obtain least-squares fits to the measured hfs constants. The results so far obtained show good self-consistency, but could profit very much from data on additional levels. As mentioned above, however, the possibility of obtaining such additional

*Consultant to Physics Division.

data depends, in turn, on the existing classification of the spectrum. A computer program is being written to make corrections for the effects of second-order hfs interactions between each state of interest and all the others, including many not yet observed.

An initial report on this work was presented[1] at the Symposium on Atomic Spectroscopy held in Tucson, Arizona in September 1979. Work on the project is continuing.

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[1] W. J. Childs, L. S. Goodman, S. A. Lee, and H. Crosswhite, Symposium on Atomic Spectroscopy (SAS - 79), Tucson, Arizona, 10-14 September 1979, organized by J. O. Stoner, Jr. (University of Arizona, 1979), p. 168.

c. Rotational Dependence of the Spin-Rotation and Hyperfine Interactions in CaF

W. J. Childs and L. S. Goodman

The molecular-beam, laser-rf, double-resonance technique has been used to make the first systematic investigation in any molecule of the dependence of the spin-rotational and hyperfine interactions on the rotational quantum number N. The CaF results[1] have been accepted for publication in both Physical Review Letters[2] and Physical Review A.[3] The relevant energy splittings were determined to ±1 kHz, a precision several thousand times better than the best previous work (1978). The results show strong N dependences for both interactions, and allow evaluation of the detailed N dependence of the parameters in the Hamiltonian for the first time. Although the effects had not been explicitly predicted previously, they are in good agreement with the basic theory, and show the need for more sophisticated ab initio calculations.

The N dependence found for the spin-rotation interaction is shown in Fig. IX-8(a); the best previous determination (1978) was 39 ± 6 MHz, and no N dependence could be seen. The corresponding results for the average hyperfine splitting are shown in Fig. IX-8(b); earlier studies have not had sufficient resolution to observe the hyperfine splittings.

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[1] W. J. Childs and L. S. Goodman, Bull. Am. Phys. Soc. 25, 13 (1980).

[2] W. J. Childs and L. S. Goodman, Phys. Rev. Lett. 44, 316 (1980)

[3] W. J. Childs and L. S. Goodman, Phys. Rev. A, accepted for publication, 1980.

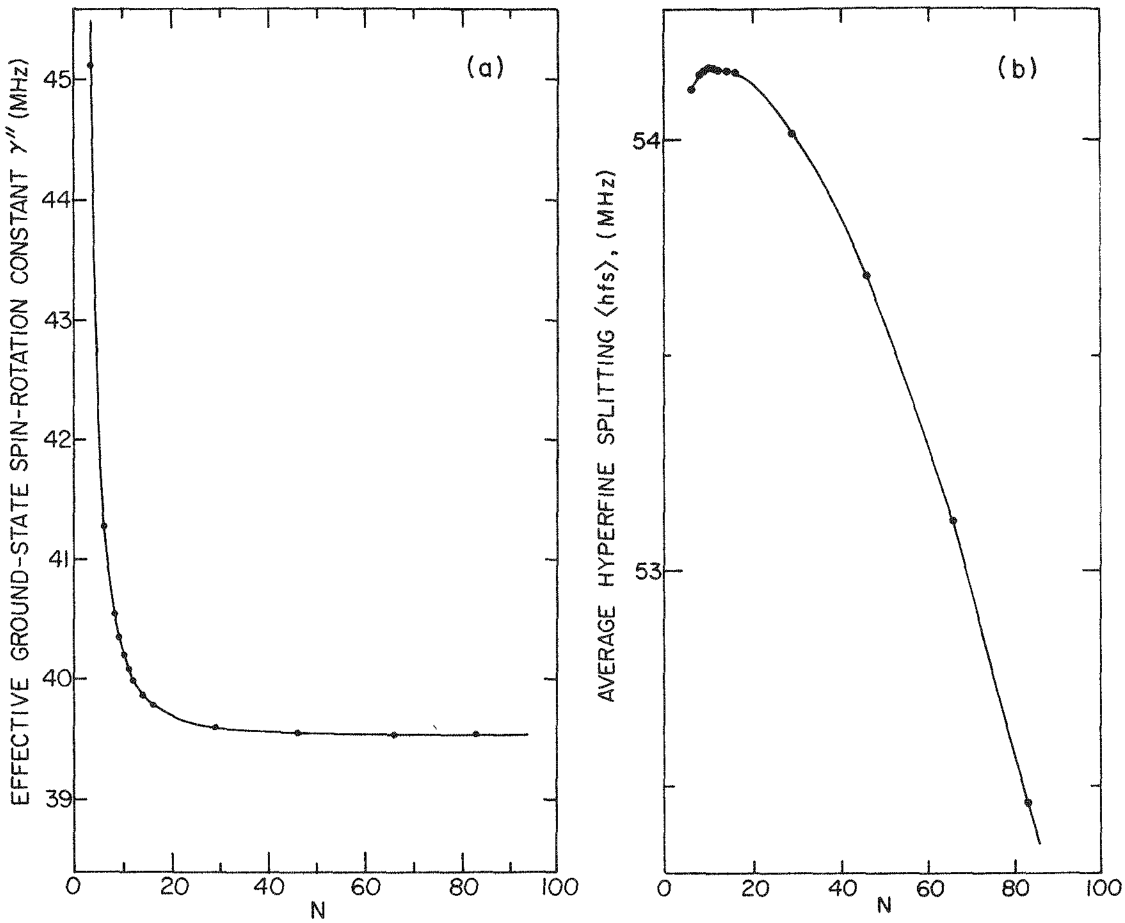

Fig. IX-8. (a) N dependence found for the spin-rotation interaction constant γ'' in the v''=0 $^2\Sigma_{1/2}$ ground state of CaF. The best previous determination (1978) of γ'' was 39 ± 6 MHz, and no N dependence could be seen. (b) Average hyperfine splitting observed in the v''=0 $^2\Sigma_{1/2}$ ground state of CaF. Earlier studies have not had sufficient resolution to observe any hfs splitting.

The success of the work suggests numerous other experiments to take full advantage of the powerful new technique to study further details of the structure of small molecules. The first such experiment to be carried out will be to extend the CaF study from the lowest (v" = 0) vibrational level of the $^2\Sigma_{1/2}$ molecular ground state to higher vibrational levels, thereby allowing evaluation of the vibrational dependence of the spin-rotation and hfs interactions. Beyond that, we plan to make analogous studies of a diatomic molecule whose ground state has some orbital angular momentum in order to analyze details of the angular momentum couplings involved.

E. MÖSSBAUER EFFECT RESEARCH

The effort during the last year has been almost entirely on the study of gamma-ray quantum beats and their applications. When a source of recoil-free gamma radiation is caused to mechanically vibrate with a period that is short compared to the lifetime of the nuclear state whose decay produced the gamma ray, the radiation is frequency modulated. The frequency-modulated quanta contain the original gamma-ray frequency and a set of "side-bands." These are frequency components spaced higher and lower in frequency by the mechanical vibration frequency. If this radiation passes through a resonant absorber and is then counted, the counting rate is observed to be time dependent. The time dependence can be studied by examining its frequency structure. The Fourier components of the spectrum of counts-vs-time have ratios which are sensitive to the energy displacement of the source and absorber resonances. This is the basis of the applications of the quantum beats made to date.

During 1979, progress was made on (1) the theory of the process, (2) a test of the sensitivity of the quantum beats method for the measurement of small shifts, by measuring the second-order Doppler shift in a Be-Fe absorber when its temperature was varied, (3) a measurement of the dependence of an isomer shift on a magnetic field, and (4) an investigation of frequency modulation techniques.

a. A Theoretical Description of Quantum Beats of Recoil-Free Gamma Radiation

J. E. Monahan and G. J. Perlow

The theory[1] treats the photon amplitude semiclassically and the absorption as an optical process in a resonant medium. The transmitted intensity is obtained as a function of the difference between the unperturbed frequency of the vibrating source and the resonant frequency of the absorber, and of the laboratory time too. This intensity $I(\omega_0-\omega_0',t)$ is used to calculate various observable properties, such as the harmonic composition of the intensity spectrum, and the prominent dispersion phenomenon observed in velocity spectra when the counting rate is restricted to events from some subinterval of the vibration cycle.

[1] J. E. Monahan and G. J. Perlow, Phys. Rev. A 20, 1499 (1979).

b. Measurement of the Second-Order Doppler Shift in Beryllium Doped with Iron by the Method of Harmonic Ratio of Gamma-Ray Quantum Beats

W. Potzel, G. J. Perlow, and J. E. Monahan

When a solid is heated, the thermal motion results in a relativistic shift toward lower energies of the energy of a nuclear resonance. The effect has been well studied in Fe-Be by ordinary Mössbauer spectroscopy, where it is readily seen for temperature changes of 50—100°C. We[1] have used the substance in a temperature controlled enclosure and have been able to resolve changes of 2°C. A time spectrum was obtained at each of 9 temperatures, spaced about 10°C apart. Each spectrum was analyzed by a computer program that fitted the spectrum to a Fourier series truncated to six terms. The ratio of the amplitudes of the fundamental to the second harmonic is the quantity that is sensitive to energy shift. This quantity when plotted vs temperature lay on a straight line, whose slope was determined. This could then be compared to a calibration in which the absorber at constant temperature was moved at various velocities. The results were in good agreement with the earlier measurements, and served to demonstrate the power of the method.

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[1] G. J. Perlow, J. E. Monahan, and W. Potzel, Suppl. J. Phys. (Paris) 41, C1-85 (1980).

c. Measurement of Magnetic Field Dependent Isomer Shifts

L. E. Campbell and G. J. Perlow

When a magnetic field is applied to a source of ^{57}Co doped into copper, the effect on the Mössbauer spectrum is to split an originally single line spectrum into a six-line Zeeman multiplet. No shift in energy would be expected between the original line position and the center of the split spectrum in the simplest description of a bare ^{57}Fe (resulting from the ^{57}Co→^{57}Fe decay) nucleus in a field. However, the field also acts on the electrons of the copper matrix, and conceivably can result in a change in electron density at the iron nucleus. This produces a net shift. Other causes of a shift are also possible. A proper understanding of the phenomena can lead to additional understanding of the interaction of an impurity ion with a host metal.

An experiment was performed by use of the quantum-beat technique. The results show a shift of 6 μm/sec in a field of 15.3 kG. The possibility that the result is an artifact caused by the split spectrum is not completely ruled out and requires further experimentation.

d. Investigation of Frequency Modulation Techniques

L. E. Campbell, G. J. Perlow, and H. E. Stanton

The traditional method for producing a frequency modulated recoil-free γ-ray source has been to vibrate the source foil by a piezo-electric crystal to which it has been cemented. When this is done, it is found that there is not a unique value of modulation index and/or vibrational phase over the dimensions of the source volume. This has a deleterious effect on the efficiency for producing quantum beats. To improve the situation, a technique common to ultrasonic measurements was tried, in which a fluid transmits the ultrasonic signal between the piezo crystal and the source foil. The spectrum of modulation indices greatly narrowed. Work is continuing.

APPLIED PHYSICS

INTRODUCTION

Although the main business of the Physics Division is basic research, we are also conducting a research program that is dedicated primarily to applied research goals. This involves the Interaction of Energetic Particles with Solids (M. Kaminsky). This applied research is carried out in conjunction with the basic research studies from which it evolved.

X. APPLIED PHYSICS

INTERACTION OF ENERGETIC PARTICLES WITH SOLIDS

This research project is designed to study specific atomic and molecular phenomena that occur when energetic ions (keV—MeV range) interact with both bulk and surfaces of solids. Particularly, fundamental studies of the mechanisms underlying (a) the release of atomic and molecular species from solid surfaces, and (b) the changes in the surface topography and in the microstructure of the implant region under energetic-particle impact are being conducted.

One main goal of these studies is to determine how well-characterized surface regions of lattices with (1) a defined low degree of lattice damage and low gas content, or with (2) a high degree of lattice damage and high gas content caused by trapping of incident ions (e.g., H^+, D^+, $^4He^+$) will affect the basic mechanisms of such fundamental atomic processes as ion/atom reflection, secondary ion and electron emission, atom/molecule release by sputtering, and energy-loss mechanisms and charge states of particles penetrating through a lattice. Information of this type is practically nonexistent for light-ion bombardment of solids. However, such information is of significant importance for (a) a better understanding of atomic collision processes, (b) analysis of older data which showed significant scatter and may have been influenced by lattice damage and incident-ion trapping, and (c) for such practical applications as fusion-plasma-impurity control and accelerator technology.

Furthermore, we are conducting studies in direct support of the national fusion-power development program (supported by OFE/DOE and Princeton University). These studies have the following four goals: (1) To identify and develop a sufficient understanding of the processes leading to plasma contaminant release, surface damage and erosion of candidate beam dump, beam limiter and first-wall materials in order to allow the selection of optimum designs. (2) To generate data on plasma contaminant release yields and the degree of surface damage and erosion of low-Z coatings and medium-Z claddings under irradiation conditions that will be meaningful for an assessment of their use for vacuum vessels, armor plates, beam limiters and calorimeters in both near-term and long-term machines. (3) To search for solutions for the control and reduction of plasma contaminant release and surface damage and erosion processes. (4) To conduct cooperative studies with major plasma laboratories in the USA and abroad in order to help in the identification of some of the major sources for, and types of plasma contaminants and surface erosion in existing plasma devices and in the next generation of devices. Some work in pursuit of these goals was carried out with Princeton's Plasma Physics Laboratory, Lawrence Livermore Laboratory and with the Kurchatov Institute in Moscow.

Finally, experiments will be designed for a search of molecular ions formed by the simultaneous interaction of two independent ion beams (e.g., H^+ and D^+ in the 10-keV—100-keV range) with solid films. Transmission and backscattering using both monocrystalline and polycrystalline films, will be studied.

The experiments are carried out with well-characterized surfaces of solids which are studied with scanning electron microscopy, transmission electron microscopy, and scanning Auger spectroscopy. The irradiations are being carried out with three different facilities.

One facility is a recently completed (1977) novel accelerator system which produces two ion beams simultaneously, and merges them on the same beam axis before permitting them to interact with solid targets at a chosen angle of incidence. This system allows (1) in situ sputtering-yield determination under ultrahigh-vacuum conditions, (2) a search for the formation of molecular species formed by the simultaneous interaction of ions of two different species (e.g., H^+, D^+) with solids, and (3) a search for interactive surface effects on the release of target particles and on target surface damage and erosion.

The second facility consists of a low-energy ion accelerator (1 keV to 15 keV). This system allows in situ determination for low ion energies under ultrahigh-vacuum conditions. Calibrated sputter-depth profiling will be used to determine the sputter deposits in situ. The third facility, upgraded during 1977/78, produced high current densities of mass analyzed ions ($\sim$10 mA/cm^2) in the 10-keV to 120-keV energy range and allows target irradiation in the ultrahigh-vacuum range.

1. A TECHNIQUE FOR DETERMINING THE DEPTH DISTRIBUTION OF CAVITIES IN He-IRRADIATED NICKEL

G. Fenske,* S. K. Das, and M. Kaminsky

In order to facilitate the experimental search for evidence of helium bubble coalescence at higher implant doses (>10^{21} ions/m^2) as a function of implant depth, it was necessary to improve a sample sectioning technique, which allows one to view (with TEM) the entire bubble depth distribution from a single specimen. The major difficulty to overcome is the tendency of etchants (and electropolishing agents) to preferentially remove material from heavily ion-damaged regions. The sectioning technique which we developed involved several steps, such as plating, spark cutting, mechanical polishing, electropolishing, and ion milling. The application of this technique allows one to determine the depth distribution of cavities

*Thesis student, University of Illinois, Urbana, Illinois.

with a high accuracy (∿50 to 100 Å). Major details of the technique were published in Ref. 1.

[1]G. Fenske, S. K. Das, and M. Kaminsky, J. Nucl. Mater. 80, 373 (1979).

2. EVIDENCE FOR THE COALESCENCE OF CAVITIES IN NICKEL IRRADIATED WITH 500-keV $^4He^+$ IONS

George Fenske,* Santosh K. Das, Manfred Kaminsky, and George Miley†

Studies of the depth distributions of dislocations and cavities (voids or bubbles) in ion irradiated metals are of great importance for an understanding of the blistering mechanisms. Different blistering models have been proposed, of which some invoke the coalescence of bubbles and the buildup of internal gas pressure as a precursor to blister appearance, while others do not. For example, some of the models based on the buildup of internal gas pressure consider the coalescence of gas bubbles as the main driving force for blister appearance, whereas the models based on the integral lateral stresses do not. It is the main goal of these studies to search for evidence for bubble coalescence in nickel irradiated at 500°C with 500-keV $^4He^+$ ions. Specifically, we want to determine at which implant depth and dose range helium bubble coalescence can be observed. The transverse sectioning technique described in Ref. 1 was used for the study of the entire depth distribution of bubbles from a single specimen.

Figure X-1(A) shows a typical bright-field micrograph of the cavity microstructure of a nickel foil implanted with 500-keV $^4He^+$ ions at 500°C to a dose of 1×10^{21} ions/m^2. The interface between the plating and the implanted region is clearly seen in this figure together with the cavities. A cavity-denuded zone near the bombarded surface extending to a depth of 0.15 to 0.2 μm can be seen. Figure X-1(B) shows a bright-field micrograph of the cavity microstructure near the peak-swelling depth of a sample implanted with a 500-keV $^4He^+$ at 500°C to a dose of 1×10^{22} ions/m^2.

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[1]G. Fenske, S. K. Das, and M. Kaminsky, J. Nucl. Mater. 80, 373 (1979).

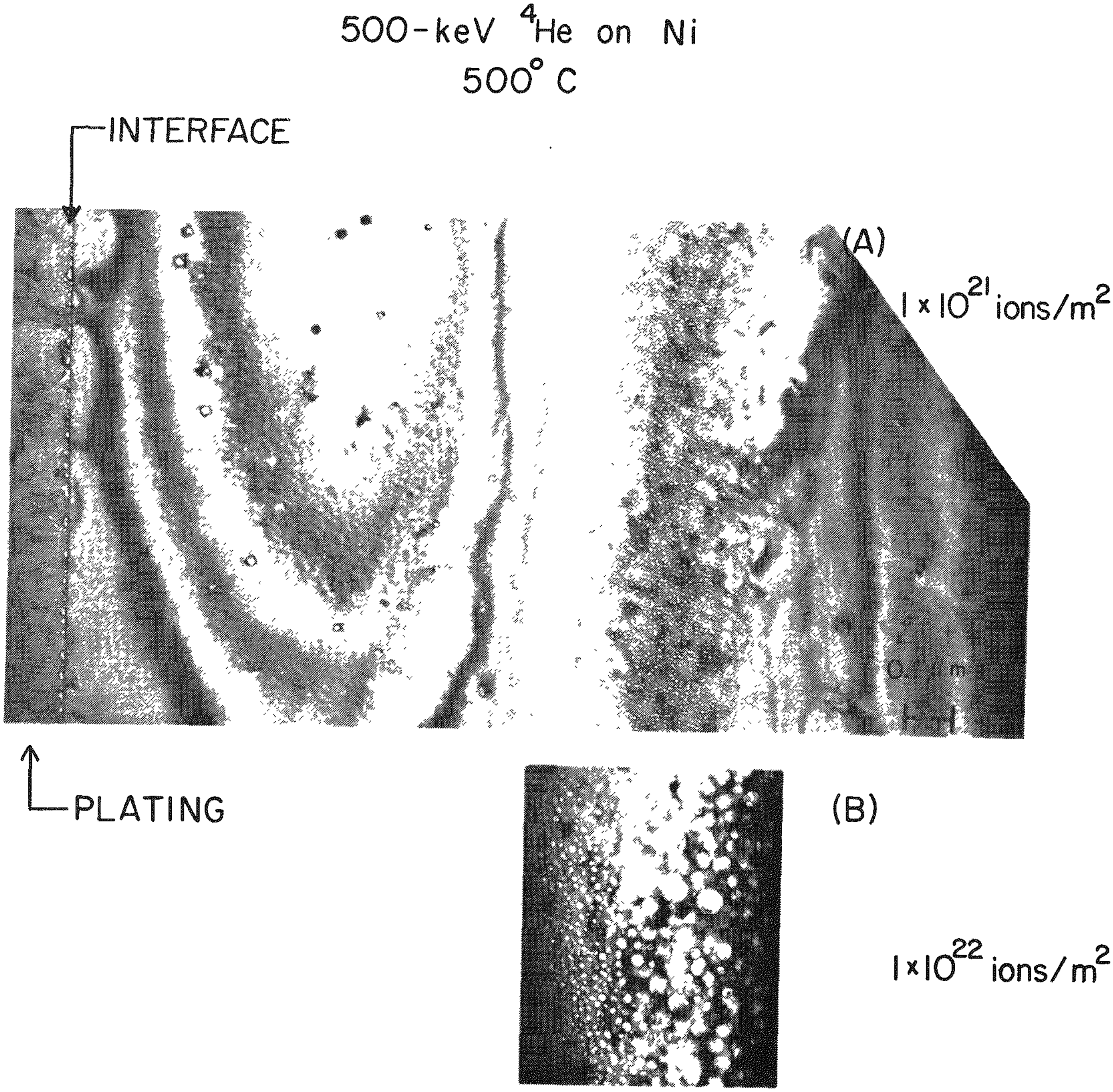

Fig. X-1. The cavity microstructure of nickel irradiated with 500-keV $^4He^+$ ions at 500°C to (a) a dose of 1×10^{21} ions/m^2, and (b) a dose of 1×10^{22} ions/m^2 (cavity structure here seen near the peak swelling depth).

The morphology changes drastically from a high density, small cavity-size microstructure to a low density, large cavity-size microstructure as the implant depth is increased from ∿0.9 μm to ∿1.1 μm. From micrographs of near-surface regions it was determined that the width of the cavity-denuded zone decreased to less than 50 nm.

Figures X-2(a) and X-2(b) show quantitative results on the variations in the average cavity-diameter and number density, and in the swelling due to cavities as a function of depth for nickel implanted with 500-keV $^4He^+$ ions at 500°C to doses of 1×10^{21} and 1×10^{22} ions/m^2, respectively. Previous results[2] have shown that at 2×10^{19} ions/m^2, the average diameter is nearly independent of the implant depth. However, as the dose was increased above 2×10^{19} ions/m^2, the average diameter was no longer independent of depth. Near the surface, the cavities were large; further in, they gradually decreased in size with increasing implant depths.

In contrast, the sample irradiated to 1×10^{22} ions/m^2 has a maximum number density at depths considerably shallower (i.e., at ∿0.8 μm) than the location of the peak in the volume swelling. Indeed, the density decreases beyond ∿0.8 μm, reaches a minimum value near the maximum swelling depth, then increases at deeper depths and eventually drops to zero at the end of the swelling profile, a trend which lies outside statistical errors. The solid and dashed curves in Figs. X-2(a) and X-2(b) show the depth distributions of the energy deposited into displacing lattice atoms by nuclear collisions, and the projected range, respectively.

These were calculated using Brice's computer programs: COREL, RASE4, and DAMG2 with theoretical LSS electronic stopping.[3,4] Comparing the swelling profiles in Figs. X-2(a) and (b), it is seen that the maximum swelling occurs at depths approximately 10% deeper than the peak in the projected-range profile.

Figure X-3 shows the average cavity-diameter, number density, and volume swelling at the maximum-swelling depths as functions of the total implant dose for nickel implanted with 500-keV $^4He^+$ ions at 500°C in the dose

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[2] G. Fenske, S. K. Das, and M. Kaminsky, J. Nucl. Mater. 85 & 86, 707 (1979).

[3] D. K. Brice, Ion Implantation Range and Energy Deposition Codes COREL, RASE4, and DAMG2, SAND 75-0622 (1977).

[4] J. Lindhard and M. Scharff, Phys. Rev. 124, 128 (1961).

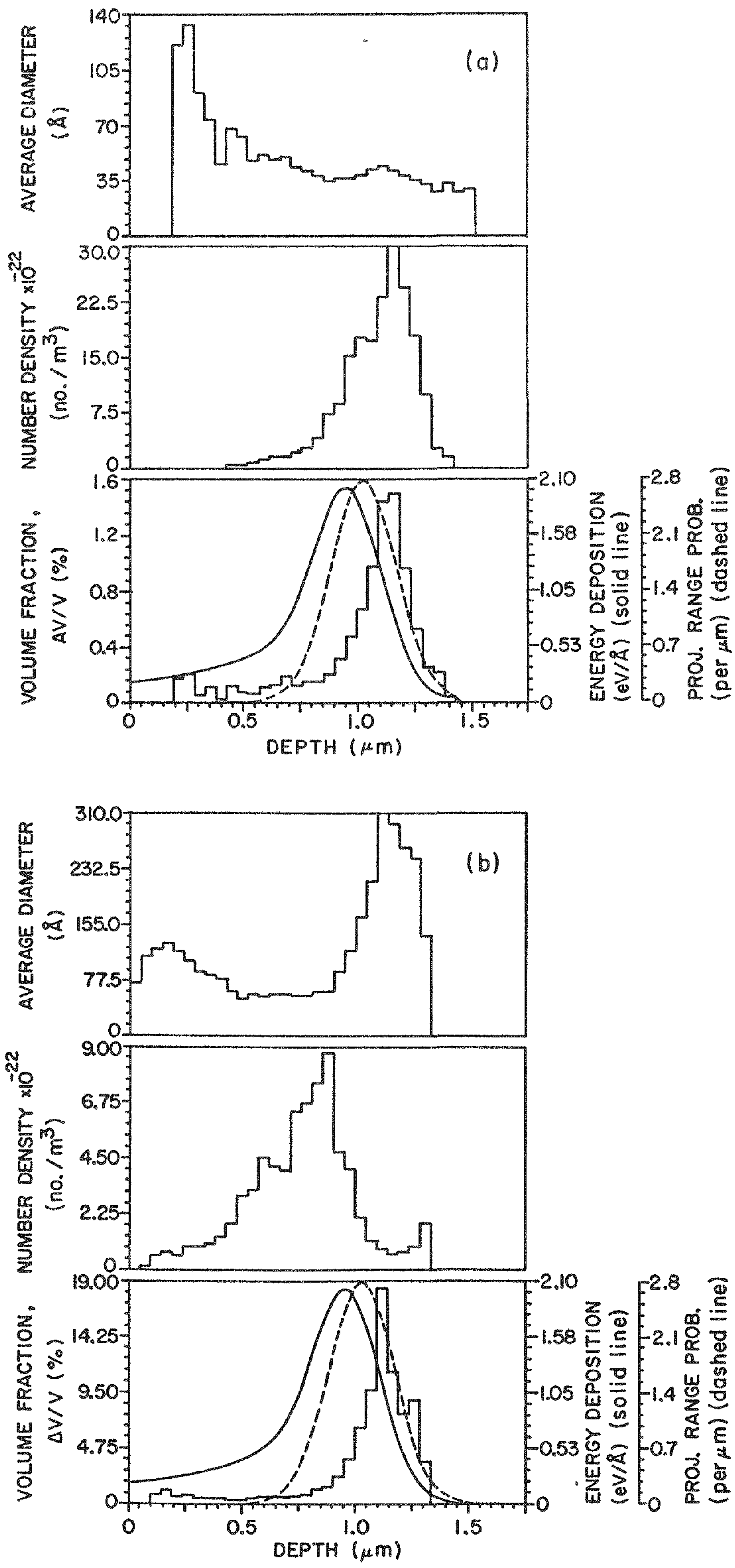

Fig. X-2. The average diameter, number density, and volume fraction of cavities as functions of depth in nickel implanted at 500°C with 500-keV $^4He^+$ ions to a dose of (a) 1 × 10^{21} ions/m^2, and (b) 1 × 10^{22} ions/m^2, respectively. The plots of volume fraction vs depth include the calculated depth distribution of projected range (dashed curve) and energy deposited into damage (solid curve).

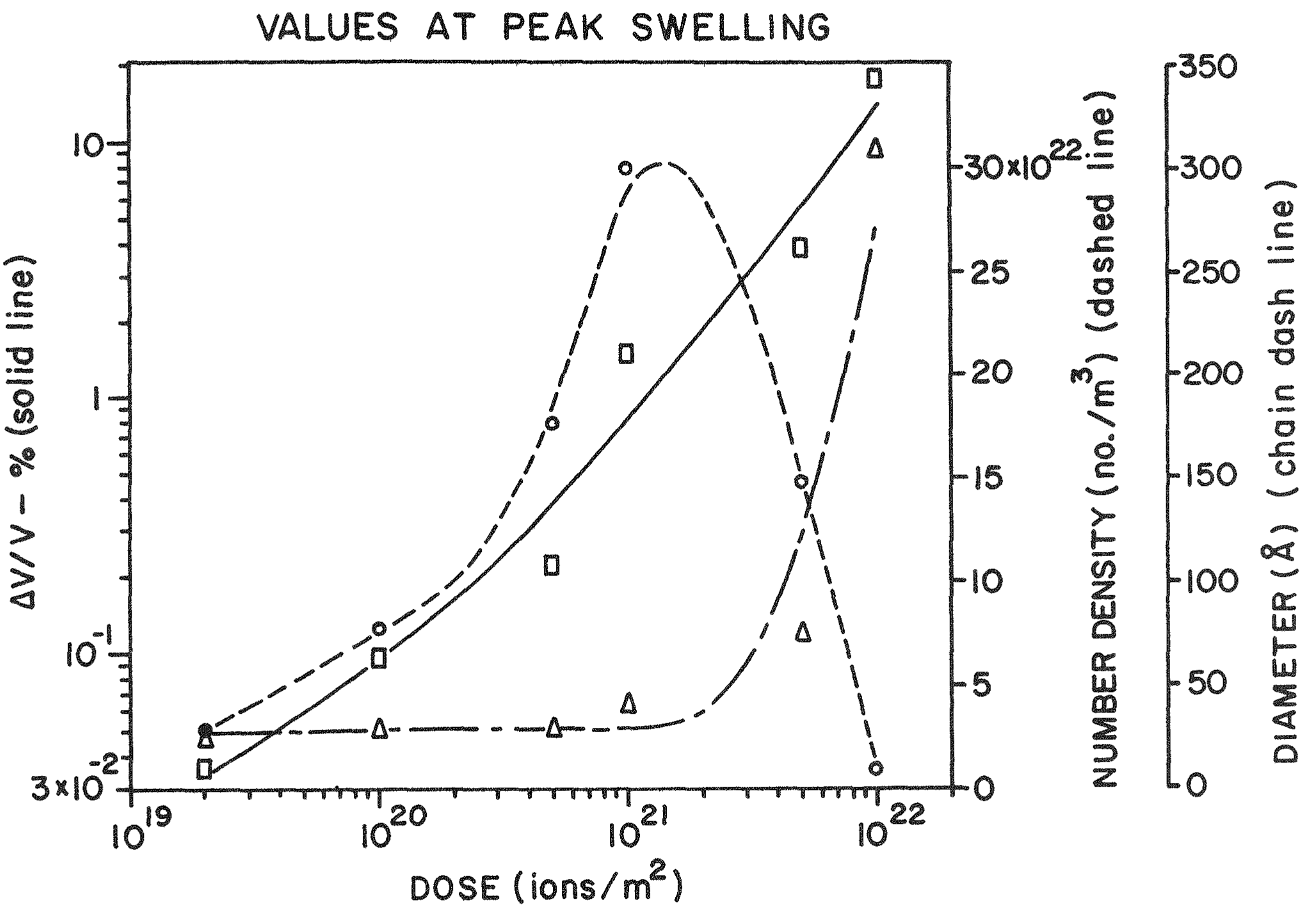

Fig. X-3. The average cavity diameter, the cavity number density, and the volume swelling at the maximum swelling depths for nickel implanted with 500-keV $^4He^+$ ions at 500°C, to doses ranging from 2×10^{19} to 1×10^{22} ions/m^2.

range from 2×10^{19} to 1×10^{22} ions/m^2. It is seen that up to 1×10^{21} ions/m^2, the cavity size remains relatively constant, while the swelling and number density increase with increasing dose. Beyond 1×10^{21} ions/m^2, the number density at the peak-swelling depths decreases with increasing dose, with corresponding increases in the average size of the cavity.

In conclusion, the reduction in the cavity density and the concurrent increase in the cavity size beyond a certain dose at the maximum-swelling depth can be interpreted as direct evidence of coalescence. An estimate indicates that a sufficient quantity of helium is available to generate helium pressures that fracture the load-bearing cross section. As such, these results demonstrate that the deformation process predicted in coalescence models is feasible. More detailed discussions of the results can be found in Ref. 5

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[5] G. Fenske, S. K. Das, M. Kaminsky, and G. Miley, Nucl. Instrum. Methods 170, 465 (1980).

3. SURFACE EFFECTS INDUCED BY SIMULATED PLASMAS

a. Deuterium and Helium Ion Irradiation Effects on TiB_2 Coatings

S. K. Das and M. Kaminsky

Coatings of low atomic number Z materials are being considered for use on first walls, limiters and armor plates of controlled thermonuclear fusion devices. Use of low Z coatings is desirable because the release of plasma contaminants with high Z from first wall components in plasma devices can cause significant increases in plasma resistivity and in plasma power losses owing to electromagnetic radiations. This in turn can prevent the ignition of fusion reactions at sufficiently high impurity concentrations. Titanium diboride, TiB_2, is one of the candidate coating materials being considered for applications in fusion device components. It can be readily chemically vapor deposited on many substrate materials (e.g., stainless steel, Kovar, copper, molybdenum and graphite) and has low to moderate Z constituents (Z = 5 and 22). In order to evaluate the suitability of TiB_2 coatings for first wall, limiter and armor plate applications, it is important to determine the effects of D^+ and He^+ bombardment on these coatings.

The surface damage and erosion of chemically vapor deposited TiB_2 coatings and commercial grade titanium, caused by 5- to 120-keV D^+ and He^+ ion irradiations for different doses at room temperature, have been studied for the "as-deposited" coatings and for coating surfaces that were mechanically polished prior to irradiation. Figure X-4 illustrates some typical results obtained for "as-deposited" TiB_2 coatings [Figs. X-4(A), (D)], for polished TiB_2 coatings [Figs. X-4(B), (E)] and for polished Ti metal before and after irradiation with 100-keV $^4He^+$ ions to a dose of 3.1×10^{18} ion/cm^2 at room temperature. One can readily notice that the surface erosion due to blister exfoliation and flaking is much more severe for the polished TiB_2 coatings and the Ti metal than for the "as-deposited" TiB_2 coating. A quantitative estimate of the erosion yield (number of TiB_2 molecules released per incident ion) for the polished TiB_2 coatings gives a value of about 0.35 ± 0.1 (molecules/ion) while the value for the "as-deposited" TiB_2 coating is more than two orders of magnitude smaller. This significant difference in yield values can in part be understood by the retardation of blister growth on rough surfaces with small size grains (as is the case for the "as-deposited" TiB_2 coating). Figure X-5 shows scanning electron micrographs of polished TiB_2 surfaces irradiated with 5-, 10-, 15-, 20-, and 100-keV $^4He^+$ [Figs. X-5(A)—5(E)] and D^+ ions [Figs. X-5(F)—5(K)]. Here one notices that the average blister diameter for both D^+ and $^4He^+$ increases with increasing ion energy, a trend which can be explained by our "gas pressure" blistering model.[1,2] Furthermore, for a given energy in this range (10—100 keV), the blister diameter for D^+ irradiation is larger than for $^4He^+$ irradiation. This is related in part to the greater depth of penetration of deuterons than for helium ions at a given energy, and more important, to the lower permeation rate for deuterium than for helium in ceramic materials such as TiB_2. Figure X-6 illustrates such differences in the blister diameters for the case of 15-keV D^+ and $^4He^+$ ion irradiation of polished TiB_2 surfaces. For more details regarding the results, see Refs. 3 and 4.

[1] M. Kaminsky and S. K. Das, The Physics of Ionized Gases, edited by R. K. Janev (Institute of Physics, Beograd, Yugoslavia, 1979), p. 401.

[2] S. K. Das and M. Kaminsky, Advances in Chemistry series 158, 112 (1976).

[3] M. Kaminsky and S. K. Das, J. Nucl. Mater. 85 & 86, 1095 (1979).

[4] S. K. Das and M. Kaminsky, Thin Solid Films 63, 269 (1979).

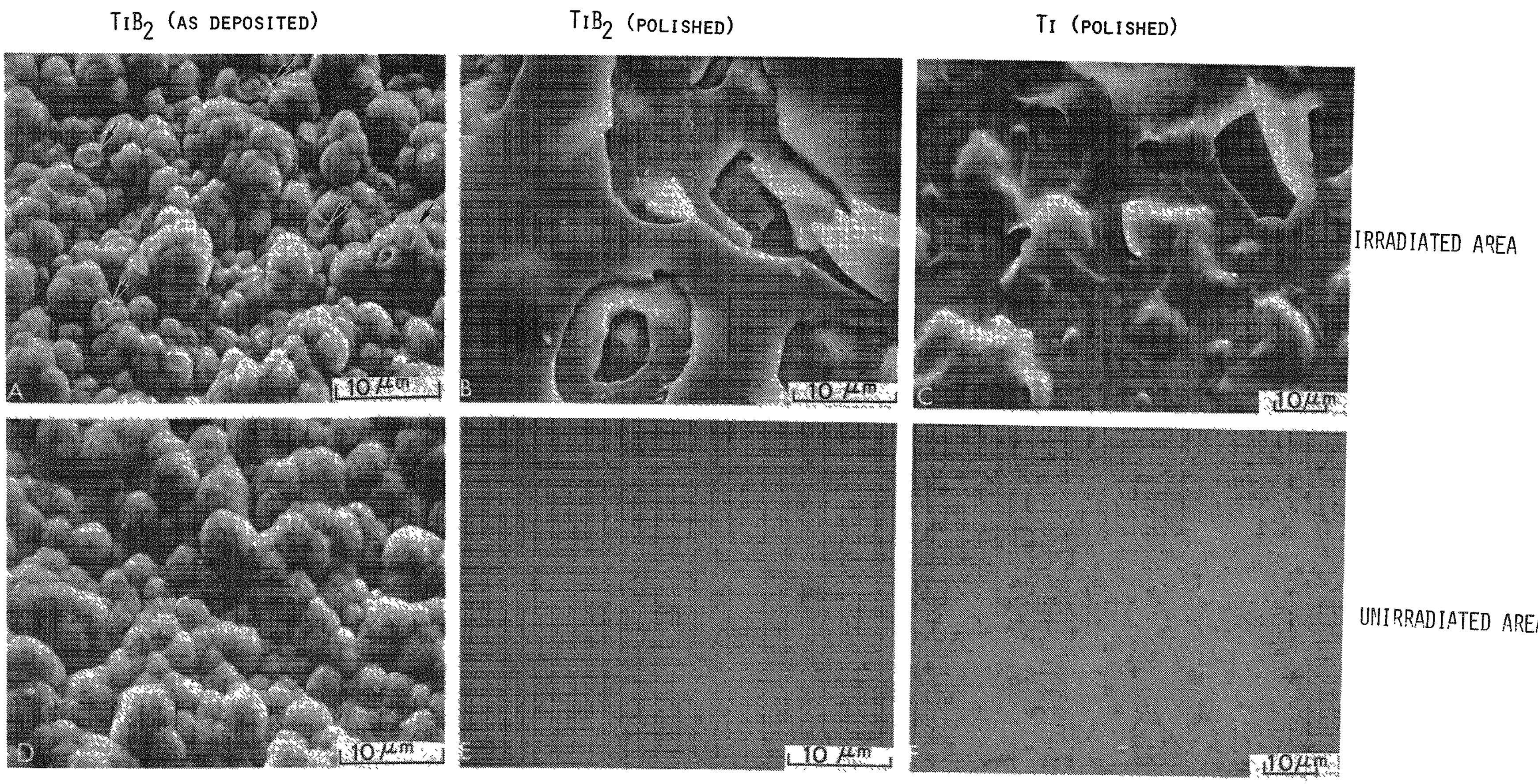

Fig. X-4. (A)—(C) SEMs of surfaces after irradiation at room temperature with 100-keV $^4He^+$ to a dose of 3.1×10^{18} ions/cm^2, (A) "as deposited" TiB_2 coating, (B) polished TiB_2 coating, and (C) polished Ti. (D)—(F) SEMs of surfaces of (D) "as deposited" TiB_2 coating, (E) polished TiB_2 coating, and (F) polished Ti before irradiation.

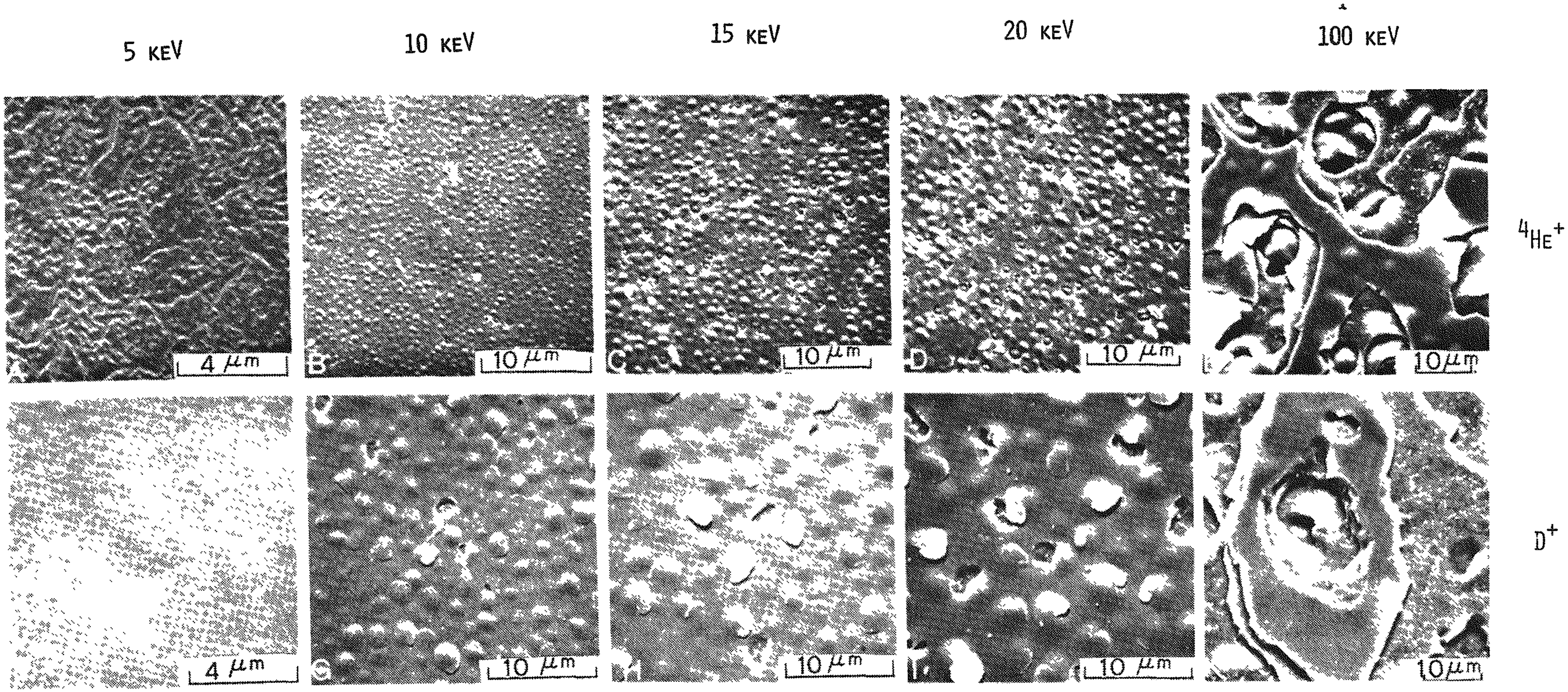

Fig. X-5. Scanning electron micrographs (SEMs) of polished TiB_2 coatings irradiated at room temperature for a dose of 3.1×10^{18} ions/cm^2 with $^4He^+$ (see A—E), and D^+ ions (F—K) for the energies indicated.

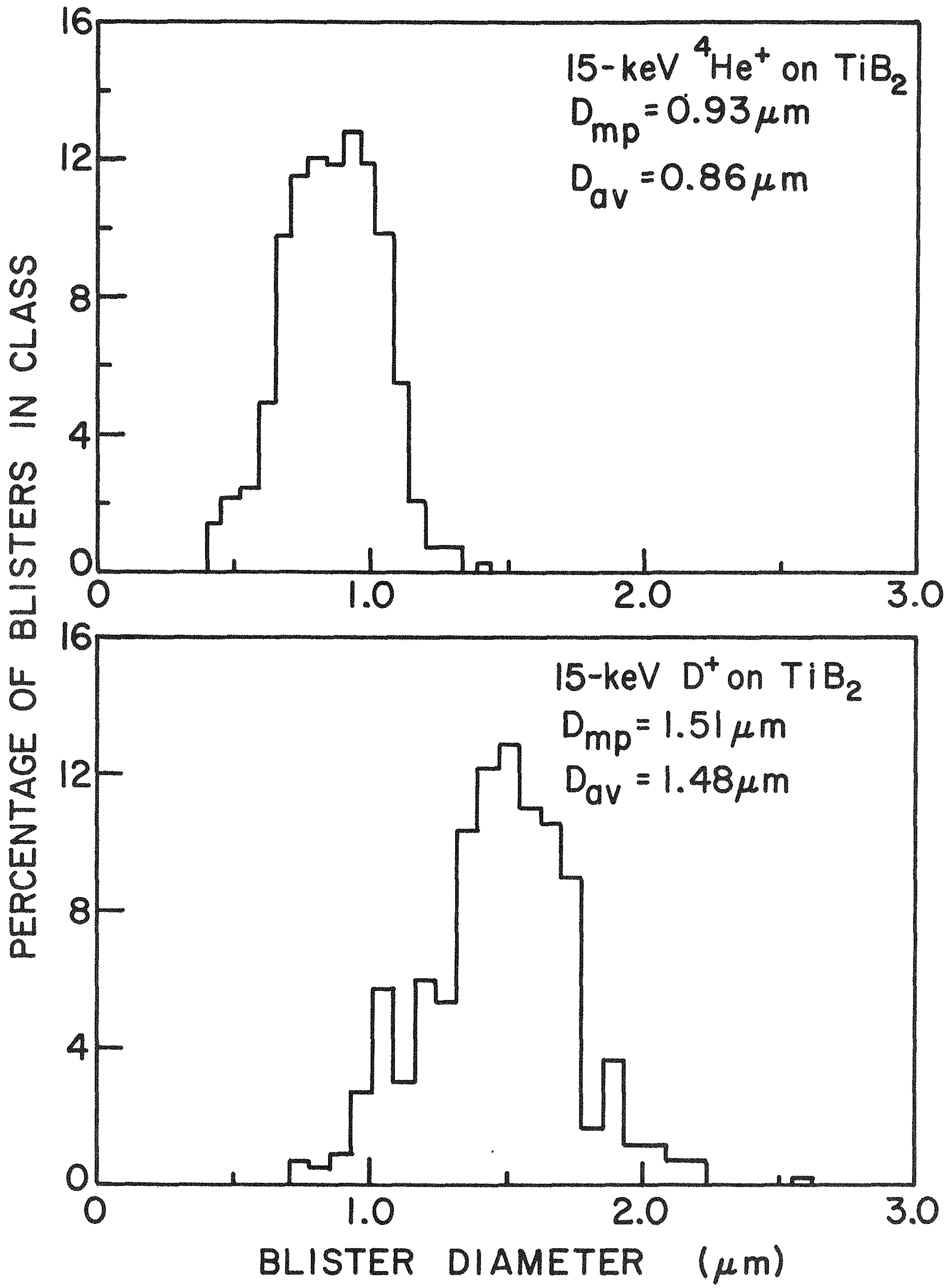

Fig. X-6. Histograms of the distributions of blister diameters for polished TiB_2 coatings irradiated at room temperature with 15-keV $^4He^+$ and D^+ to a dose of 3.1×10^{18} ions/cm^2.

b. Carbon Coatings for Fusion Applications

S. K. Das, M. Kaminsky, L. H. Rovner,* J. Chin,* and K. Chen*

The use of low atomic number, Z, materials such as carbon for protective coatings of first walls and first wall components has been considered desirable to reduce plasma contamination with high-Z materials. Furthermore, a coating process adaptable to application in situ would have the special advantage of eliminating any need for reactor disassembly to repair or refurbish the coating.

We have investigated a deposition process involving the discharge activated deposition of carbon coatings from methane at about 1 Pa pressure. A coating of thickness 10 μm on copper has survived 1000 cycles of pulsed thermal heating at 37 MW m^{-2} with only minor flaking. The surface damage of similar coatings on stainless steel surfaces has been investigated for irradiation with 20-, 40-, 60-, and 120-keV D^+ and He^+ ions at ambient temperature. Scanning electron microscopy of irradiated surfaces revealed no significant surface damage for either D^+ or He^+ irradiation with energies of 40 and 60 keV for doses of 4×10^{22} and 8.1×10^{22} ions m^{-2}, respectively, as illustrated in Figs. X-7 and X-8. For 120-keV D^+ and He^+ irradiations for a dose of 22×10^{23} ions m^{-2}, surface damage in the form of ridges was observed. A comparison of the results for carbon coatings with those obtained for ATJ graphite reveals that this type of graphite shows surface damage for all irradiations performed, while the carbon coating appears to be more resistant to damage for many of these irradiations. These results reflect favorably on the possible use of these coatings on various components in the plasma chamber of a fusion reactor. More details regarding the results can be found in Refs. 1 and 2.

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*General Atomic Company, San Diego, California.

[1] S. K. Das, M. Kaminsky, J. Chin, K. Y. Chen, and L. H. Rovner, Thin Solid Films 63, 227 (1979).

[2] M. Kaminsky and S. K. Das, J. Nucl. Mater. 85 & 86, 1095 (1979).

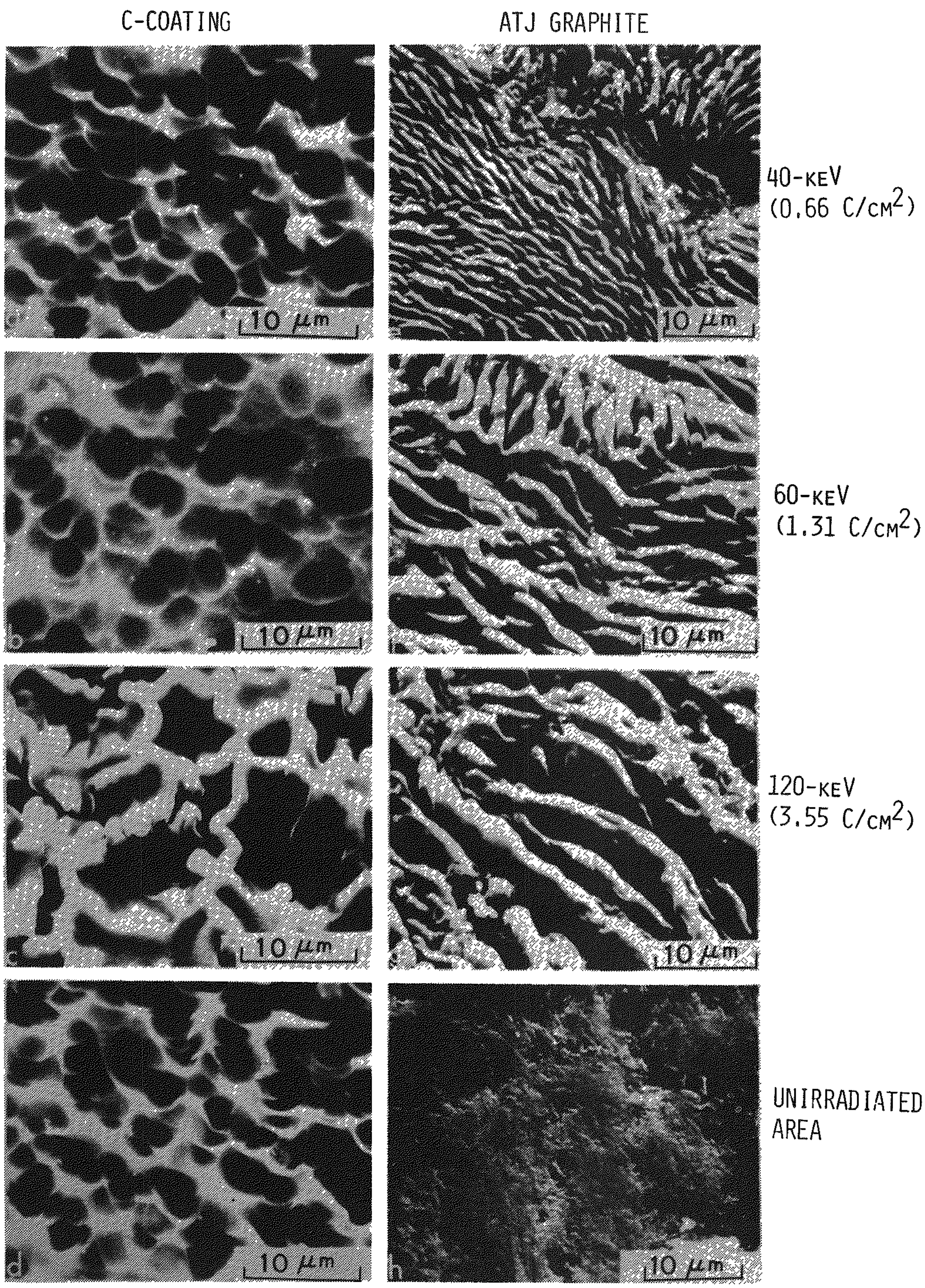

Fig. X-7. SEMs of carbon coated on stainless steel and ATJ graphite irradiated at ambient temperature with D^+ ions.

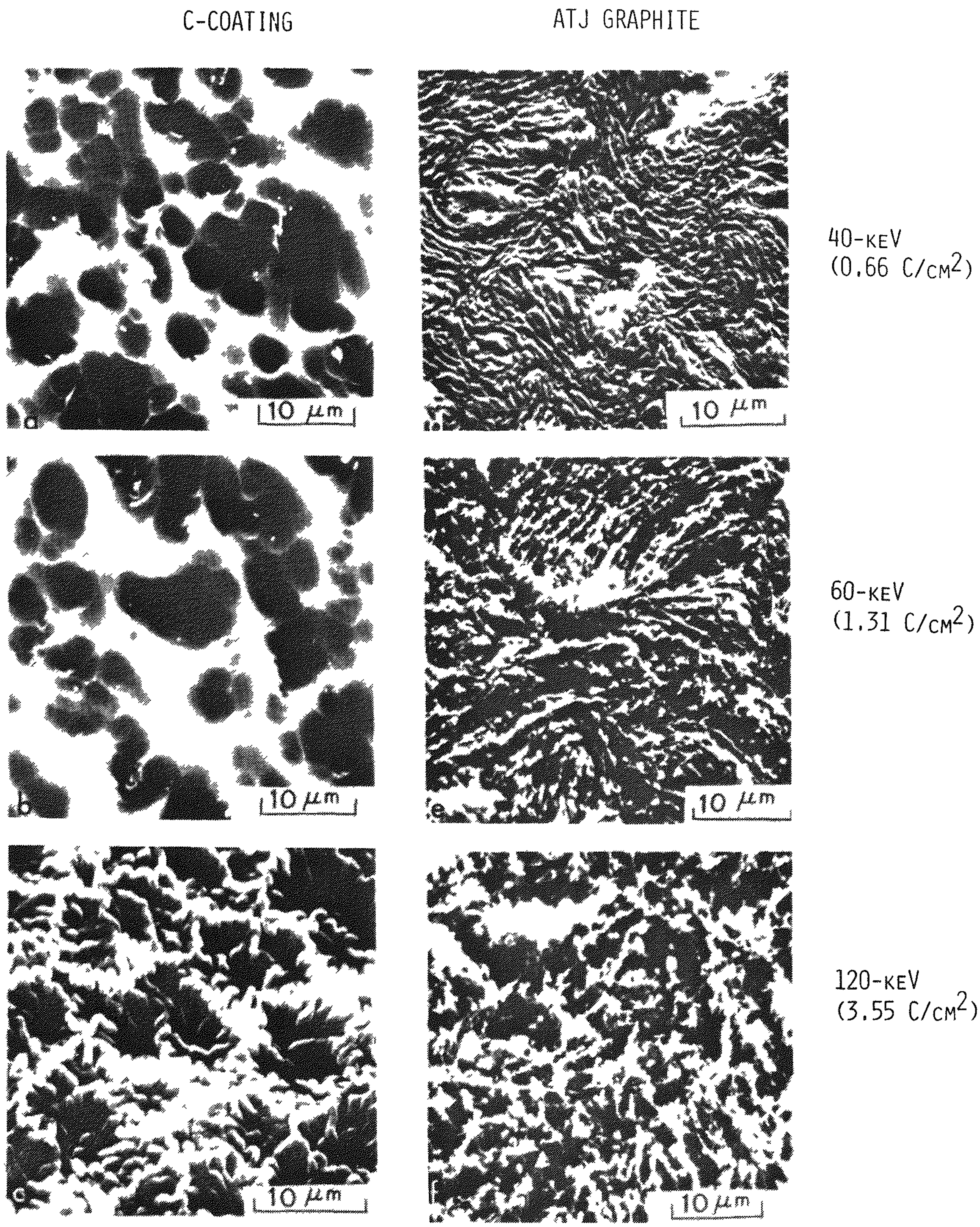

Fig. X-8. SEMs of carbon coated on stainless steel and ATJ graphite irradiated at ambient temperature with He^+ ions.

c. Cladded Materials for Fusion Applications

M. Kaminsky

This program was initiated during the first quarter of 1979. The effort is being conducted in support of Princeton University's Tokamak Fusion Test Reactor and is directed toward the following main goals:

(1) Develop cladded materials for the protection of a first wall ("Armor Plates") against a single fault condition of a plasma-neutral beam system resulting in a single radiation pulse of high power deposition ($\sim$8 kW/cm^2) for a pulse length of probably less than 0.1 sec (actual pulse length not yet established).

(2) Develop cladded materials for fixed and movable limiters, which will be exposed to repeated radiation pulses (1.0 sec pulse length, 300 sec pulse repetition period—recently, the desired pulse length was increased to 1.5 sec) with power densities of 1 to 4 kW/cm^2 under normal operating conditions.

(3) Develop claddings for the armor plate and limiter applications mentioned above, with materials which have low to medium atomic number (Z), and exhibit good adhesion, adequate heat shock resistance, acceptable thermal cycling fatigue life (for limiter applications), low outgassing rates at operating temperature, low vapor pressure at operating temperature, low sputtering yields, low surface erosion yields (e.g., erosion by blister exfoliation, chemical erosion processes, sputtering), and acceptable hydrogen isotope recycling characteristics.

Feasibility tests of our explosion cladded samples of 0.12 in. thick Nb on 0.5 in. thick OFHC copper with respect to heat shock resistance were conducted at PPPL (M. Ulrickson) and at Berkeley (R. Pyle and K. Berkner). At PPPL the samples did withstand a 0.5 sec pulse of electrons with a power deposition of 6.5 kW/cm^2, a very encouraging result. Similarly, the results at Berkeley, conducted with a 100-keV H^0 beam pulse of 0.5 sec (at 75 sec pulse rep. rate) to a power deposition of 1.4 kW/cm^2 also yielded very encouraging results. Therefore, the development program for cladded materials was started. Initially, two laminar claddings are being developed to provide protection against repetitive pulses with power densities of 2 to 4 kW/cm^2 for a pulse length of 1.5 sec and a pulse repetitive time of 300 sec. Heat transfer calculations indicate that 0.020 in. thick Ti or V sheets cladded on 0.5 in. thick OFHC copper plates may handle such repetitive power depositions. Therefore, such explosively bonded Ti/Cu and V/Cu samples were prepared successfully, and are, at the present, being characterized and tested.

PUBLICATIONS FROM 1 APRIL 1979 THROUGH 31 MARCH 1980

The list of "journal articles and book chapters," is classified by topic; the arrangement is approximately that followed in the Table of Contents of this Annual Review. The "reports at meetings" include abstracts, summaries, and full texts in volumes of proceedings; they are listed chronologically.

A. BOOKS

1. PHOTOABSORPTION, PHOTOIONIZATION, AND PHOTOELECTRON SPECTROSCOPY
   Joseph Berkowitz
   Academic Press, Inc., New York, New York, 1979

2. NUCLEAR SPECTROSCOPY (Proceedings of the Workshop, Gull Lake, Michigan, 27 August-7 September 1979)
   edited by G. F. Bertsch* and D. Kurath
   Springer-Verlag, Berlin-Heidelberg, 1980

3. PROCEEDINGS OF THE WORKSHOP ON SPUTTERING CAUSED BY PLASMA (NEUTRAL BEAM) SURFACE INTERACTION, Argonne National Laboratory, Argonne, Illinois, 9-10 July 1979, CONF-790775
   edited by J. N. Smith, Jr.† and M. Kaminsky
   National Technical Information Service, Springfield, Virginia, 1980

B. PUBLISHED JOURNAL ARTICLES AND BOOK CHAPTERS

1. MEASUREMENT OF TENSOR POLARIZATION AND CROSS SECTION FOR THE REACTION $^2H(\pi^+,\pi^+)^2H$ AT 180°
   R. J. Holt, J. R. Specht, E. J. Stephenson, B. Zeidman, R. L. Burman,‡ J. S. Frank,‡ M. J. Leitch,‡ J. D. Moses,‡ M. A. Yates-Williams,‡ R. M. Laszewski,§ and R. P. Redwine‖
   Phys. Rev. Lett. 43, 1229-1232 (22 October 1979)

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†General Atomic Co., San Diego, California.

‡Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

§University of Illinois, Urbana, Illinois.

‖Massachusetts Institute of Technology, Cambridge, Massachusetts.

2. ELASTIC AND INELASTIC SCATTERING OF 162 MeV PIONS BY ^{28}Si, ^{58}Ni AND ^{208}Pb
   C. Olmer, D. F. Geesaman, B. Zeidman, S. Chakravarti, T.-S. H. Lee, R. L. Boudrie,* R. H. Siemssen,† J. F. Amann,‡ C. L. Morris,‡ H. A. Thiessen,‡ G. R. Burleson,§ M. J. Devereux,§ R. E. Segel,‖ and L. W. Swenson¶
   Phys. Rev. C 21, 254-271 (January 1980)

3. EXCITATION OF HIGH-SPIN PARTICLE-HOLE STATES IN ^{28}Si BY PION INELASTIC SCATTERING
   C. Olmer, B. Zeidman, D. F. Geesaman, T.-S. H. Lee, R. E. Segel,‖ L. W. Swenson,¶ R. L. Boudrie,* G. S.Blanpied,§ H. A. Thiessen,‡ C. L. Morris,‡ and R. E. Anderson‡
   Phys. Rev. Lett. 43, 612-615 (27 August 1979)
   Erratum: Phys. Rev. Lett. 43, 1137 (8 October 1979)

4. ^{16}O SCATTERING FROM THE EVEN-A Mg AND Si ISOTOPES
   H. T. Fortune, A. Richter, R. H. Siemssen, and J. L. Yntema
   Phys. Rev. C 20, 648-654 (August 1979)

5. HYBRID FOCAL PLANE DETECTORS FOR HEAVY IONS
   H. W. Fulbright** and J. R. Erskine
   Nucl. Instrum. Methods 162, 355-370 (1-15 June 1979)
   + Chap. VII in Detectors in Nuclear Science, edited by D. Allan Bromley (North-Holland, 1979), pp. 355-370 [Reprinted from Nucl. Instrum. Methods 162, 355 (1979)]

6. SYSTEMATICS OF CARBON- AND OXYGEN-INDUCED FUSION ON NUCLEI WITH $12 \leq A \leq 19$
   D. G. Kovar, D. F. Geesaman, T. H. Braid, Y. Eisen, W. Henning, T. R. Ophel, M. Paul, K. E. Rehm, S. J. Sanders, P. Sperr, J. P. Schiffer, S. L. Tabor, S. Vigdor, B. Zeidman, and F. W. Prosser, Jr.
   Phys. Rev. C 20, 1305-1331 (October 1979)

7. ENERGY DEPENDENCE OF THE FUSION AND ELASTIC SCATTERING OF ^{16}O + ^{40}Ca
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   Phys. Rev. C 20, 2147-2169 (December 1979)

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8. SUPERALLOWED FERMI DECAY OF ^{62}Ga
C. N. Davids, C. A. Gagliardi, M. J. Murphy, and E. B. Norman
Phys. Rev. C <u>19</u>, 1463-1466 (April 1979)

9. CROSS SECTIONS FOR THE ^{6}Li(p,^{3}He)^{4}He REACTION AT ENERGIES BETWEEN 0.1 AND 3.0 MeV
A. J. Elwyn, R. E. Holland, C. N. Davids, L. Meyer-Schützmeister, F. P. Mooring, and W. Ray, Jr.
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10. d + ^{6}Li REACTIONS AT LOW ENERGY
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Phys. Rev. C <u>19</u>, 2114-2120 (June 1979)

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+ Chap. VIII in <u>Detectors in Nuclear Science</u>, edited by D. Allan Bromley (North-Holland, 1979), pp. 371-378 [Reprinted from Nucl. Instrum. Methods <u>162</u>, 371 (1979)]

12. REACTION ^{15}N(t,p)^{17}N
H. T. Fortune,* G. E. Moore,* L. Bland,* M. E. Cobern,* S. Mordechai,* R. Middleton,* and R. D. Lawson
Phys. Rev. C <u>20</u>, 1228-1235 (October 1979)

13. SINGLE PARTICLE NATURE OF THE YRAST LINE AT HIGH ANGULAR MOMENTUM IN ^{152}Dy
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Phys. Lett. <u>84B</u>, 178-181 (18 June 1979)

14. THE EQUATION OF STATE NEAR β EQUILIBRIUM FOR A COLLAPSING STELLAR CORE
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15. MEASUREMENT OF ULTRACOLD NEUTRONS PRODUCED BY USING DOPPLER-SHIFTED BRAGG REFLECTION AT A PULSED-NEUTRON SOURCE
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Phys. Lett. <u>75A</u>, 223-224 (7 January 1980)

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‡Solid State Science Division, ANL.

§Intense Pulsed Neutron Source Program Division, ANL.

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**University of Missouri, Columbia, Missouri.

16. PRODUCTION OF ULTRA-COLD NEUTRONS USING DOPPLER-SHIFTED BRAGG SCATTERING AND AN INTENSE PULSED NEUTRON SPALLATION SOURCE
T. W. Dombeck,* J. W. Lynn,* S. A. Werner,† T. Brun,‡ J. Carpenter,‡ V. Krohn, and R. Ringo
Nucl. Instrum. Methods 165, 139-155 (1979)

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\+ Ph.D. Thesis, University of Chicago, 1980

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M. Danos§ and J. Rafelski
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24. NUCLEAR CHARGE DEPENDENT INTERACTIONS IN THE 1p SHELL
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25. INELASTIC PION SCATTERING FOR 1p-SHELL TARGETS
T.-S. H. Lee and D. Kurath
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§National Bureau of Standards, Washington, D.C.

26. INELASTIC PION SCATTERING FROM ^{18}O
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29. TROUBLES WITH NONLEPTONIC CHARM DECAYS
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32. THEORETICAL DESCRIPTION OF QUANTUM BEATS OF RECOIL-FREE γ RADIATION
J. E. Monahan and G. J. Perlow
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45. ASYMPTOTIC DEUTERON D-STATE DETERMINATION FROM T_{22} MEASUREMENTS IN d + p ELASTIC SCATTERING
E. J. Stephenson, H. E. Conzett,** P. von Rossen,** F. Hinterberger,†† and F. Seiler‡‡
Bull. Am. Phys. Soc. 24, 569 (April 1979)

Radiation Research (Proceedings of the Sixth International Congress of Radiation Research, Tokyo, Japan, 13-19 May 1979), edited by S. Okada, M. Imamura, T. Terashima, and H. Yamaguchi (University of Tokyo, Japan, 1979)

46. INTERACTIONS OF FAST MOLECULAR IONS WITH MATTER
D. S. Gemmell
pp. 132-144

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*Florida State University, Tallahassee, Florida.

†University of Georgia, Athens, Georgia.

‡University of Massachusetts, Amherst, Massachusetts.

§Indiana University, Bloomington, Indiana.

‖Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

¶Chemistry Division, ANL.

**Lawrence Berkeley Laboratory, Berkeley, California.

††University of Bonn, Bonn, Germany.

‡‡University of Basel, Basel, Switzerland.

Topical Conference on Computerized Data-Acquisition Systems in Particle and Nuclear Physics, Santa Fe, New Mexico, 14-17 May 1979

47. THE SUPPORT OF MULTIPLE DATA STREAMS IN A DYNAMICALLY CONFIGURED SOFTWARE SYSTEM
    Joseph E. Kulaga and John W. Tippie*
        IEEE Trans. Nucl. Sci. NS-26(4), 4489-4493 (August 1979)
        + Program of the Conference, Abstract 16-D1

48. DESIGN CONSIDERATIONS FOR A MULTIPROCESSOR BASED DATA ACQUISITION SYSTEM
    John W. Tippie* and Joseph E. Kulaga
        IEEE Trans. Nucl. Sci. NS-26(4), 4548-4551 (August 1979)
        + Program of the Conference, Abstract 22-E2

Spring Meeting of the Solid State and Atomic Physics Section of the Danish Physical Society, Middelfart, Denmark, 28-29 May 1979 (Danish Physical Society, 1979)

49. LASER-rf DOUBLE-RESONANCE SPECTROSCOPY: APPLICATIONS FOR ATOMIC-STRUCTURE ANALYSIS AND NUCLEAR MOMENTS
    W. J. Childs, O. Poulsen, and L. S. Goodman
        p. 24

Summary of the Proceedings of the Workshop on Future Directions in Nuclear Physics Research, Boulder, Colorado, 30 May-2 June 1979

50. NUCLEAR SPECTROSCOPY
    D. F. Geesaman
        pp. 53-58

51. HEAVY-ION REACTIONS AT ENERGIES UP TO A FEW TENS OF MeV/NUCLEON
    W. Henning
        pp. 38-42

27th Annual Conference on Mass Spectrometry and Allied Topics, Seattle, Washington, 3-8 June 1979

52. PHOTOELECTRON SPECTROSCOPY OF PHTHALOCYANINE VAPORS
    J. Berkowitz
        Proceedings, edited by A. G. Harrison (American Society for Mass Spectrometry, 1979), pp. 96-97
        + Program of the Conference, p. 44

53. PES OF HIGHER TEMPERATURE VAPORS
    J. Berkowitz and C. H. Batson
        Proceedings, pp. 58-59
        + Program of the Conference, p. 34

54. ANGULAR DISTRIBUTIONS IN MOLECULAR ION DISSOCIATIONS OBSERVED BY PHOTOELECTRON-PHOTOION COINCIDENCE SPECTROSCOPY
    J. H. D. Eland
        Proceedings, pp. 322-323
        + Program of the Conference, p. 91

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*Applied Mathematics Division, ANL.

Mass Spectrometry and Allied Topics, Seattle, June 1979 (contd.)

55. PHOTOELECTRON SPECTRA OF TRINUCLEAR METAL CLUSTER COMPLEXES
William C. Trogler* and J. Berkowitz
Proceedings, pp. 163-164
+ Program of the Conference, p. 58

International Conference on Nuclear Physics with Electromagnetic Interactions, Mainz, Germany, 5-9 June 1979 (Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, W. Germany, 1979)

56. PHOTON SCATTERING BY THE GIANT DIPOLE RESONANCE IN MEDIUM WEIGHT NUCLEI
T. J. Bowles, R. J. Holt, H. E. Jackson, R. M. Laszewski,† R. D. McKeown, A. M. Nathan,† J. R. Specht, and R. Starr†
Abstracts of Contributed Papers, p. 4.5

57. HIGH RESOLUTION PHOTONEUTRON STUDY OF E1 AND M1 EXCITATIONS IN ^{208}Pb
R. J. Holt, H. E. Jackson, R. M. Laszewski, and J. R. Specht
Abstracts of Contributed Papers, p. 4.12

58. ALPHA PARTICLE CAPTURE THROUGH THE GIANT ELECTRIC RESONANCES IN ^{58}Ni AND ^{90}Zr
L. Meyer-Schützmeister and R. E. Segel*
Abstracts of Contributed Papers, p. 5.9

<u>Laser Spectroscopy IV</u> (Proceedings of the Fourth International Conference, Rottach-Egern, Germany, 11-15 June 1979), edited by H. Walther and K. W. Rothe (Springer-Verlag, Berlin/Heidelberg, 1979)

59. LASER-rf DOUBLE-RESONANCE SPECTROSCOPY
W. J. Childs, L. S. Goodman, and O. Poulsen
pp. 566-572

Proceedings of the Workshop on Sputtering Caused by Plasma (Neutral Beam) Surface Interaction, Argonne National Laboratory, Argonne, Illinois, 9-10 July 1979, edited by J. N. Smith, Jr. and M. Kaminsky (National Technical Information Service, Springfield, Va., 1980), CONF-790775

60. ANGULAR DISTRIBUTION OF SPUTTERED PARTICLES
M. Kaminsky
pp. 10-1—10-8

61. NEUTRON SPUTTERING
M. Kaminsky
pp. 13-1—13-7

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*Northwestern University, Evanston, Illinois.

†University of Illinois, Urbana, Illinois.

Eleventh EGAS (European Group for Atomic Spectroscopy) Conference, Paris-Orsay, France, 10-13 July 1979, Summaries of Contributions (European Physical Society, 1979)

62. LASER-rf DOUBLE-RESONANCE STUDIES OF ATOMIC STRUCTURES AND NUCLEAR MOMENTS IN URANIUM
W. J. Childs, O. Poulsen, and L. S. Goodman
p. 51

Proceedings of the Symposium on Heavy Ion Physics from 10 to 200 MeV/AMU, Brookhaven National Laboratory, Upton, New York, 16-20 July 1979, edited by J. Barrette and P. D. Bond (National Technical Information Service, Springfield, Va., 1979), Brookhaven National Laboratory Report BNL-51115

63. HEAVY-ION-LINAC POST-ACCELERATORS
Lowell M. Bollinger
Vol. 2, pp. 589-625

64. QUASIELASTIC REACTIONS
W. Henning
Vol. 1, pp. 445-470

65. HEAVY-ION DIRECT-REACTION MECHANISMS—THE SPECTROSCOPIC APPROACH
Malcolm H. Macfarlane
Vol. 2, pp. 673-711

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66. NEUTRAL HYDROGEN FROM THE FOIL-INDUCED DISSOCIATION OF $^{4}HeH^{+}$, $^{3}HeH^{+}$, AND H_2^+
Patrick J. Cooney, Donald S. Gemmell, Elliot P. Kanter, Werner J. Pietsch, and Bruce J. Zabransky
Nucl. Instrum. Methods 170, 73-77 (1980)
\+ Atomic Collisions in Solids (Proceedings of the Conference), pp. 73-77 [Reprinted from Nucl. Instrum. Methods 170, 73-77 (1980)]

67. EVIDENCE FOR THE COALESCENCE OF CAVITIES IN NICKEL IRRADIATED WITH 500-keV $^{4}He^{+}$ IONS
George Fenske, Santosh K. Das, Manfred Kaminsky, and George Miley*
Nucl. Instrum. Methods 170, 465-470 (1980)
\+ Atomic Collisions in Solids, pp. 465-470 [Reprinted from Nucl. Instrum. Methods 170, 465-470 (1980)]

68. THE COLLISION INDUCED FRAGMENTATION OF FAST MOLECULAR IONS IN SOLIDS AND GASES
Donald S. Gemmell
Nucl. Instrum. Methods 170, 41-56 (1980)
\+ Atomic Collisions in Solids, pp. 41-56 [Reprinted from Nucl. Instrum. Methods 170, 41-56 (1980)]

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*University of Illinois, Urbana, Illinois.

Atomic Collisions in Solids, Hamilton, August 1979 (contd.)

69. DETERMINATION OF MOLECULAR-ION STRUCTURES THROUGH STUDIES OF THE COLLISIONALLY INDUCED DISSOCIATION OF FAST (MeV) MOLECULAR IONS
Donald S. Gemmell, Patrick J. Cooney, and Elliot P. Kanter
Nucl. Instrum. Methods 170, 81-85 (1980)
+ Atomic Collisions in Solids, pp. 81-85 [Reprinted from Nucl. Instrum. Methods 170, 81-85 (1980)]

70. EXPERIMENTAL CONFIRMATION OF THE JAHN-TELLER DISTORTION OF CH_4^+
Donald S. Gemmell, Elliot P. Kanter, and Werner J. Pietsch
Nucl. Instrum. Methods 170, 79-80 (1980)
+ Atomic Collisions in Solids, pp. 79-80 [Reprinted from Nucl. Instrum. Methods 170, 79-80 (1980)]

71. MEASUREMENT OF THE DISTRIBUTIONS OF INTERNUCLEAR SEPARATIONS IN 3.0-MeV H_2^+ AND 3.63-MeV HeH^+ BEAMS
Elliot P. Kanter, Patrick J. Cooney, Donald S. Gemmell, Zeev Vager, Werner J. Pietsch, and Bruce J. Zabransky
Nucl. Instrum. Methods 170, 87-91 (1980)
+ Atomic Collisions in Solids, pp. 87-91 [Reprinted from Nucl. Instrum. Methods 170, 87-91 (1980)]

72. THE TRANSMISSION OF FAST MOLECULAR IONS THROUGH THIN FOILS
Werner J. Pietsch, Donald S. Gemmell, Patrick J. Cooney, Elliot P. Kanter, Dieter Kurath, Anthony J. Ratkowski, Zeev Vager, and Bruce J. Zabransky
Nucl. Instrum. Methods 170, 61-66 (1980)
+ Atomic Collisions in Solids, pp. 61-66 [Reprinted from Nucl. Instrum. Methods 170, 61-66 (1980)]

8th International Conference on High Energy Physics and Nuclear Structure, Vancouver, Canada, 13-17 August 1979

73. PROPERTIES OF PION SINGLE CHARGE EXCHANGE REACTIONS IN NUCLEI
T. J. Bowles, D. F. Geesaman, R. J. Holt, H. E. Jackson, R. M. Laszewski, J. R. Specht, E. J. Stephenson, R. E. Segel,* R. P. Redwine,† M. A. Yates-Williams,† and J. Julien‡
Abstracts of Contributed Papers, edited by D. F. Measday (University of British Columbia, Vancouver, 1979), p. 42

74. OBSERVATION OF THE CROSS SECTION AND TENSOR POLARIZATION IN π-d ELASTIC SCATTERING AT 180°
R. J. Holt, J. R. Specht, E. J. Stephenson, B. Zeidman, R. L. Burman,† J. S. Frank,† M. J. Leitch,† J. D. Moses,† M. A. Yates-Williams,† R. M. Laszewski,§ and R. P. Redwine‖
Abstracts of Contributed Papers, p. 3

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*Northwestern University, Evanston, Illinois.

†Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

‡C.E.N., Saclay, France.

§University of Illinois, Urbana, Illinois.

‖Massachusetts Institute of Technology, Cambridge, Massachusetts.

High Energy Physics and Nuclear Structure, Vancouver, August 1979 (contd.)

75. PION REACTION MODES ON NUCLEI
J. P. Schiffer
Nucl. Phys. A335, 339-352 (18 February 1980)
+ High Energy Physics and Nuclear Structure (Proceedings of the Conference), edited by D. F. Measday and A. W. Thomas (North-Holland, Amsterdam, 1980), pp. 339-352 [Reprinted from Nucl. Phys. A335, 339-352 (1980)]

76. PION INELASTIC SCATTERING TO 6- STATES IN ^{28}Si
B. Zeidman, C. Olmer, T. S. H. Lee, D. F. Geesaman, R. E. Segel,* L. W. Swenson,† R. Anderson,‡ R. L. Boudrie,‡ C. L. Morris,‡ H. A. Thiessen,‡ and G. S. Blanpied§
Abstracts of Contributed Papers, p. 37

Proceedings of the Workshop on Physics with Fast Molecular-Ion Beams, Argonne National Laboratory, Argonne, Illinois, 20-21 August 1979, edited by D. S. Gemmell, Physics Division Informal Report ANL/PHY-79-3 (August 1979)

77. OPTICAL MEASUREMENTS OF MOLECULAR DISSOCIATION BY THIN FOILS
H. G. Berry
pp. 259-267

78. RECENT WORK WITH FAST MOLECULAR-ION BEAMS AT ARGONNE NATIONAL LABORATORY
P. J. Cooney, D. S. Gemmell, K.-O. Groeneveld, E. P. Kanter, W. J. Pietsch, Z. Vager, and B. J. Zabransky
pp. 53-85

79. OPTICAL OBSERVATIONS OF MOLECULAR DISSOCIATION IN THIN FOILS
T. J. Gay and H. G. Berry
pp. 279-289

80. PROBING THE WAKE OF A SWIFT ION IN MATTER
W. J. Pietsch,‖ G. Krösing,¶ G. Kumbartzki,¶ and D. S. Gemmell
pp. 179-192

Nuclear Spectroscopy (Proceedings of the Workshop, Gull Lake, Michigan, 27 August-7 September 1979), edited by G. F. Bertsch and D. Kurath (Springer-Verlag, Berlin-Heidelberg, 1980)

81. THE NUCLEAR SHELL MODEL
D. Kurath
pp. 45-68

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*Northwestern University, Evanston, Illinois.

†Oregon State University, Corvallis, Oregon.

‡Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

§New Mexico State University, Las Cruces, New Mexico.

‖University of Cologne, Cologne, Germany.

¶University of Bonn, Bonn, Germany.

XIV European Congress on Molecular Spectroscopy, Frankfurt/Main, Germany, 3-7 September 1979

82. THE STRUCTURE OF MOLECULAR IONS STUDIED WITH FAST (MeV) HEAVY PROJECTILES
K. O. Groeneveld,* H. J. Frischkorn,* S. Schumann,* D. S. Gemmell, P. J. Cooney, E. P. Kanter, and W. J. Pietsch†
J. Mol. Structure 60, 85-88 (1980)

Symposium on Atomic Spectroscopy (SAS - 79), Tucson, Arizona, 10-14 September 1979, organized by J. O. Stoner, Jr. (University of Arizona, 1979)

83. Hfs OF MANY LOW ATOMIC LEVELS OF ^{141}Pr BY LASER-rf DOUBLE RESONANCE
W. J. Childs, L. S. Goodman, S. A. Lee, and H. Crosswhite
pp. 168-169

84. WAVELENGTHS AND TRANSITION PROBABILITIES IN SIX- AND SEVEN-TIMES IONIZED KRYPTON
L. J. Curtis,‡ A. E. Livingston, R. M. Schectman,‡ and H. G. Berry
p. 74

85. WAVELENGTHS AND FINE STRUCTURE OF THE 2s-2p TRANSITIONS IN TWO- AND THREE-ELECTRON IONS
R. DeSerio, H. G. Berry, and A. E. Livingston
p. 101

86. DESTRUCTION OF MOLECULAR BEAM-FOIL COLLISION INDUCED ALIGNMENT
T. J. Gay and H. G. Berry
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87. ^{138,139}La NUCLEAR ELECTRIC-QUADRUPOLE MOMENT RATIO BY LASER-rf DOUBLE RESONANCE
L. S. Goodman and W. J. Childs
pp. 166-167

International Conference on Mössbauer Spectroscopy, Portoroz, Yugoslavia, 10-14 September 1979

88. QUANTUM BEATS OF RECOIL-FREE γ RADIATION
G. J. Perlow, J. E. Monahan, and W. Potzel§
Suppl. J. Phys. (Paris) 41, C1-85—93 (1980)

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*Institut für Kernphysik, J. W. Goethe-Universität, Frankfurt, Germany.

†University of Köln, Köln, Germany.

‡University of Toledo, Toledo, Ohio.

§Technical University, Munich, Germany.

Proceedings of the 1979 Linear Accelerator Conference, Mantuak, New York, 10-14 September 1979, edited by R. L. Witkover (Brookhaven National Laboratory, Upton, New York, 1980), Brookhaven National Laboratory Report BNL-51134

89. STATUS OF THE ARGONNE SUPERCONDUCTING-LINAC HEAVY-ION ENERGY BOOSTER
J. Aron,* R. Benaroya, L. M. Bollinger, B. E. Clifft,* W. Henning, K. W. Johnson,* J. M. Nixon,* P. Markovich,* and K. W. Shepard
pp. 104-108

Division of Nuclear Physics, American Physical Society, Knoxville, Tennessee, 18-20 October 1979

90. INCLUSIVE PION SINGLE CHARGE EXCHANGE REACTIONS IN NUCLEI
H. E. Jackson
Bull. Am. Phys. Soc. 24, 824 (September 1979)

91. SAMPLING METHODS FOR THE MONTE CARLO CALCULATIONS OF MODEL NUCLEAR MATTER
M. H. Kalos,† B. D. Day, and J. G. Zabolitzky
Bull. Am. Phys. Soc. 24, 849 (September 1979)

Division of Electron and Atomic Physics, American Physical Society, Houston, Texas, 10-12 December 1979

92. ORIENTATION-DEPENDENT ELECTRON CAPTURE FOLLOWING THE FOIL-INDUCED DISSOCIATION OF SWIFT MOLECULAR IONS
P. J. Cooney, D. S. Gemmell, and E. P. Kanter
Bull. Am. Phys. Soc. 24, 1200 (November 1979)

93. WAVELENGTHS AND TRANSITION PROBABILITIES IN SIX- AND SEVEN-TIMES IONIZED KRYPTON
L. J. Curtis,‡ A. E. Livingston,§ R. M. Schectman,‡ and H. G. Berry
Bull. Am. Phys. Soc. 24, 1204 (November 1979)

94. WAVELENGTHS AND FINE STRUCTURE OF 2s-2p TRANSITIONS IN TWO- AND THREE-ELECTRON IONS
A. E. Livingston,§ H. G. Berry, R. R. DeSerio, S. J. Hinterlong,§ and J. A. Poirier§
Bull. Am. Phys. Soc. 24, 1191 (November 1979)

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*Chemistry Division, ANL.

†New York University, New York, New York.

‡University of Toledo, Toledo, Ohio.

§University of Notre Dame, Notre Dame, Indiana.

American Physical Society, Chicago, Illinois, 21-24 January 1980

95. HIGH-PRECISION LASER-rf DOUBLE-RESONANCE SPECTROSCOPY OF THE $^{2}\Sigma$ GROUND STATE OF CaF
W. J. Childs and L. S. Goodman
Bull. Am. Phys. Soc. 25, 13 (January 1980)

96. AN 11-SECOND ISOMER IN ^{72}Br
C. N. Davids, D. F. Geesaman, M. J. Murphy, E. B. Norman, and S. L. Tabor
Bull. Am. Phys. Soc. 25, 46-47 (January 1980)

97. CROSS SECTIONS FOR THE $^{6}Li(^{3}He,p)2\alpha$ REACTION AT LOW ENERGIES
A. J. Elwyn, R. E. Holland, C. N. Davids, F. P. Mooring, J. E. Monahan, and W. J. Ray
Bull. Am. Phys. Soc. 25, 47 (January 1980)

98. SCATTERING OF 291-MeV PIONS BY NUCLEI
D. F. Geesaman, C. Olmer, B. Zeidman, R. L. Boudrie,* H. A. Thiessen,† M. Devereux,‡ G. L. Blanpied,‡ G. R. Burleson,‡ L. W. Swenson,§ and R. E. Segel‖
Bull. Am. Phys. Soc. 25, 47 (January 1980)

99. SPIN-ROTATIONAL AND HYPERFINE STRUCTURE IN THE $^{2}\Sigma^{+}$ GROUND STATE OF CaF
G. L. Goodman
Bull. Am. Phys. Soc. 25, 13 (January 1980)

100. THE STATE OF THE MEASUREMENT OF THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON
G. R. Ringo
Bull. Am. Phys. Soc. 25, 27 (January 1980)

101. NUCLEAR DENSITY INFORMATION FROM PION SCATTERING
B. Zeidman
Bull. Am. Phys. Soc. 25, 22 (January 1980)

American Physical Society, New York, New York, 24-28 March 1980

102. STEREOCHEMICAL STRUCTURES OF MOLECULAR IONS DETERMINED THROUGH "COULOMB EXPLOSION" TECHNIQUES WITH FAST (MeV) MOLECULAR-ION BEAMS
D. S. Gemmell
Bull. Am. Phys. Soc. 25, 425-426 (March 1980)

103. MODIFICATION OF SURFACES FOR CONTROL OF PLASMA IMPURITY RELEASE AND SURFACE EROSION
M. S. Kaminsky
Bull. Am. Phys. Soc. 25, 423 (March 1980)

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*University of Colorado, Boulder, Colorado.

†Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

‡New Mexico State University, Las Cruces, New Mexico.

§Oregon State University, Corvallis, Oregon.

‖Northwestern University, Evanston, Illinois.

D. PHYSICS DIVISION REPORTS

1. STUDY OF A NATIONAL 2 GeV CONTINUOUS BEAM ELECTRON ACCELERATOR
Y. Cho,* R. J. Holt, H. E. Jackson, T. K. Khoe,* and G. S. Mavrogenes†
Physics Division Informal Report ANL-PHY-79-2 (October 1979)

2. PROCEEDINGS OF THE WORKSHOP ON PHYSICS WITH FAST MOLECULAR-ION BEAMS, Argonne National Laboratory, Argonne, Illinois, 20-21 August 1979
edited by D. S. Gemmell
Physics Division Informal Report ANL/PHY-79-3 (August 1979)

3. PROCEEDINGS OF THE SYMPOSIUM ON HIGH-SPIN PHENOMENA IN NUCLEI, Argonne National Laboratory, Argonne, Illinois, 15-17 March 1979
organized by W. Henning, T. L. Khoo, D. Kurath, and J. P. Schiffer
Physics Division Informal Report ANL/PHY-79-4 (October 1979)

4. COMPUTER SIMULATION OF ION ORBITS IN THE ARGONNE SUPERCONDUCTING HEAVY-ION LINAC (TEST VERSION)
Murray Peshkin
Physics Division Informal Report ANL-PHY-79-1 (May 1979)

E. PATENT

FOCAL-SURFACE DETECTOR FOR HEAVY IONS
John R. Erskine, Thomas H. Braid,‡ and Joseph C. Stoltzfus§
U.S. Patent No. 4,150,290 (17 April 1979)

---

*Accelerator Research Facilities Division, ANL.

†Chemistry Division, ANL.

‡Reactor Analysis and Safety Division, ANL.

§Beloit College, Beloit, Wisconsin.

STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the permanent staff of the Physics Division for the year ending 31 March 1980. The program heading indicates only the individual's current primary activity.

EXPERIMENTAL NUCLEAR PHYSICS

Scientific Staff

[†]Lowell M. Bollinger, Ph.D., Cornell University, 1951

[‡]Cary N. Davids, Ph.D., California Institute of Technology, 1967

[§]Alexander J. Elwyn, Ph.D., Washington University, 1956

[||]John R. Erskine, Ph.D., University of Notre Dame, 1960

Donald F. Geesaman, Ph.D., State University of New York, Stony Brook, 1976

Walter Henning, Ph.D., Technical University, Munich, 1968

Robert E. Holland, Ph.D., University of Iowa, 1950

Roy J. Holt, Ph.D., Yale University, 1972

Harold E. Jackson, Jr., Ph.D., Cornell University, 1959

Teng Lek Khoo, Ph.D., McMaster University, 1972

Dennis G. Kovar, Ph.D., Yale University, 1971

Victor E. Krohn, Ph.D., Case Western Reserve University, 1952

[¶]Alexander Langsdorf, Jr., Ph.D., Massachusetts Institute of Technology, 1937

[¶]John J. Livingood, Ph.D., Princeton University, 1929

Robert D. McKeown, Ph.D., Princeton University, 1979

[**]Luise Meyer-Schützmeister, Ph.D., Technical University of Berlin, 1943

[†]In charge of Superconducting Linac Project.

[‡]Full time at Argonne. Also Senior Visiting Research Associate at the Enrico Fermi Institute, University of Chicago through September 1979.

[§]In charge of Dynamitron accelerator operations.

[||]Temporarily at D.O.E. Headquarters, Washington, D.C. (December 1977—December 1979).

[¶]Retired-consultant.

[**]Temporarily assigned to Max Planck Institute, Heidelberg, Germany (October 1979—September 1980).

†John P. Schiffer, Ph.D., Yale University, 1954

Richard C. Pardo, Ph.D., University of Texas, 1976

G. Roy Ringo, Ph.D., University of Chicago, 1940

†John P. Schiffer, Ph.D., Yale University, 1954

Kenneth W. Shepard, Ph.D., Stanford University, 1970

Robert K. Smither, Ph.D., Yale University, 1956

‡J. L. Yntema, Ph.D., Free University of Amsterdam, 1952

Benjamin Zeidman, Ph.D., Washington University, 1957

Technical and Engineering Staff

Ralph Benaroya

John J. Bicek

Patric K. Den Hartog

William F. Evans

Joseph E. Kulaga

*James W. Lamka

James R. Specht

James L. Stadelmann

George E. Thomas, Jr.

James N. Worthington

THEORETICAL PHYSICS

Scientific Staff

§Arnold R. Bodmer, Ph.D., Manchester University, 1953

Fritz Coester, Ph.D., University of Zurich, 1944

Benjamin Day, Ph.D., Cornell University, 1963

Dieter Kurath, Ph.D., University of Chicago, 1951

Robert D. Lawson, Ph.D., Stanford University, 1953

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*No longer at Argonne as of 31 March 1980.

†Director of the Physics Division; Associate Director through September 1979. Joint appointment with the University of Chicago.

‡In charge of Tandem accelerator operations.

§Joint appointment with the University of Illinois, Chicago Circle Campus.

[†]Tsung-Shung Harry Lee, Ph.D., University of Pittsburgh, 1973

[†]Malcolm H. Macfarlane, Ph.D., University of Rochester, 1959

James E. Monahan, Ph.D., St. Louis University, 1953

[‡]Murray Peshkin, Ph.D., Cornell University, 1951

Steven C. Pieper, Ph.D., University of Illinois, 1970

EXPERIMENTAL ATOMIC AND MOLECULAR PHYSICS

Scientific Staff

Joseph Berkowitz, Ph.D., Harvard University, 1955

[§]H. Gordon Berry, Ph.D., University of Wisconsin, 1967

William J. Childs, Ph.D., University of Michigan, 1956

[*]Santosh K. Das, Ph.D., University of California, 1971

[*]John H. D. Eland, D. Phil., Oxford University, 1966

Donald S. Gemmell, Ph.D., Australian National University, 1960

[‖]Leonard S. Goodman, Ph.D., University of Chicago, 1952

Manfred S. Kaminsky, Ph.D., University of Marburg, 1957

[*]Siu Au Lee, Ph.D., Stanford University, 1976

[¶]Gilbert J. Perlow, Ph.D., University of Chicago, 1940

Stanley L. Ruby, B.A., Columbia University, 1947

Technical and Engineering Staff

Charles H. Batson

John A. Dalman

Robert W. Nielsen

Walter J. Ray

Bruce J. Zabransky

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[*]No longer at Argonne as of 31 March 1980.

[†]Joint appointment with the University of Chicago.

[‡]Deputy Director of the Physics Division; Acting Director through September 1979.

[§]Joint appointment with the University of Chicago through September 1979.

[‖]Assistant Director of the Physics Division through September 1979.

[¶]Joint appointment as Editor of the Applied Physics Letters.

ADMINISTRATIVE STAFF

†Albert J. Hatch, M.S., University of Illinois, 1947

†F. Paul Mooring, Ph.D., University of Wisconsin, 1951

From 1 April 1979 through 31 March 1980 there were 40 temporary staff members and visitors (including 17 postdoctoral appointees), 13 graduate students, and 6 undergraduates. These temporary appointments in the Physics Division are listed below.

TEMPORARY APPOINTMENTS

Postdoctoral Appointees

Michel E. Betz (from Massachusetts Institute of Technology, Cambridge, Massachusetts): Effects of the Δ-isobar decay width on the properties of nucleon-nucleon scattering and nuclear matter. (September 1977— November 1979)

Thomas J. Bowles (from Princeton University, Princeton, New Jersey): Investigation of weak neutral currents in nuclei; study of inclusive pion single charge exchange photonuclear physics; development of NaI detectors; study of charge dependent effects. (October 1976— July 1979)

Robert L. Brooks (from University of Alberta, Alberta, Canada): Fast ion spectroscopy. (August 1979—)

Partha Chowdhury (from State University of New York, Stony Brook, New York): Studies of high-spin states of nuclei. (November 1979—)

Hartmut J. H. Ernst (Technical University of Munich, Munich, Germany): Heavy-ion reaction studies. (Alexander v. Humboldt Foundation Fellowship.) (January 1980—)

Christopher M. Jachcinski (from State University of New York, Stony Brook, New York): Heavy-ion reactions: particularly, $^{16}O + ^{24,26}Mg$ and $^{24}Mg + ^{24}Mg$ fusion. (October 1979—)

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†Assistant Director of the Physics Division.

Elliot P. Kanter (from Rutgers University, New Brunswick, New Jersey): Study of the interaction of fast molecular ion beams with matter. (September 1977—August 1979)

Raymond E. Kutina (from University of Toronto, Toronto, Canada): Photoionization of free radicals. (March 1980—)

Siu-Kwong Lam (from University of Windsor, Canada): Surface studies by means of Auger spectroscopy and other probes. (November 1976—December 1979)

Padma Marikar (from University of Birmingham, Birmingham, England): Development of cladding materials for the fusion reactors; surface erosion studies. (May 1979—December 1979)

Catherine Olmer (from Lawrence Berkeley Laboratory, Berkeley, California): Research in nuclear physics concerning nature of reaction mechanisms and structure of nuclei. (August 1977—August 1979)

Michael Paul (from Hebrew University of Jerusalem, Israel): Study of resonances in heavy-ion reactions. (August 1977—September 1979)

Mark J. Rhoades-Brown (from University of Surrey, England): Heavy-ion direct reaction studies with particular emphasis on developing mathematical techniques to enable large scale coupled-channel calculations to be carried out. (October 1977—)

Stephen J. Sanders (from Yale University, New Haven, Connecticut): Experimental medium-energy and heavy-ion physics research. (September 1977—)

Edward J. Stephenson (from Lawrence Berkeley Laboratory, Berkeley, California): Medium-energy physics experiments and related activities. (February 1978—August 1979)

Kenneth E. Stephenson (from University of Wisconsin, Madison, Wisconsin): Pion-nucleus reaction mechanisms. (September 1979—)

Owen K.-T. Wu (from University of Illinois, Urbana, Illinois): Surface studies with SEM, SIM, and SAM techniques. (April 1979—August 1979)

Long-Term Visitors (at Argonne more than 4 months)

Jørn Borggreen (Niels Bohr Institute, Copenhagen, Denmark): Gamma-ray studies at the ANL superconducting linac. (August 1979—)

Patrick J. Cooney (Middlebury College, Middlebury, Vermont): Interaction of swift molecular-ion beams with matter. (July 1978—August 1979)

Walter Kutschera (Technical University of Munich, Munich, Germany): Nuclear research and accelerator development. (August 1978—)

*Harry J. Lipkin (Weizmann Institute of Science, Rehovot, Israel): Theoretical nuclear and particle physics. (June 1979—)

Bogumila Myslek-Laurikainen (Institute of Nuclear Research, Swierk, Poland): Parity violation in the 5.1-MeV J=2 doublet of ^{10}B. (December 1978—)

Itzhak Plesser (Weizmann Institute of Science, Rehovot, Israel): Interaction of fast molecular ions with solid target: (1) molecular structure gained through this interaction; (2) various aspects of the interaction itself—wake, multiple scattering, transmission, etc. (August 1979—)

R. G. Hamish Robertson (Michigan State University, East Lansing, Michigan): Experimental studies of parity violation in ^{10}B and ^{6}Li. (January 1980—)

Resident Graduate Students

Lambros Arnellos (University of Illinois, Chicago Circle Campus, Chicago, Illinois): Calculations of high-energy heavy-ion collisions. (June 1979—)

Soumya Chakravarti (University of Chicago, Chicago, Illinois): Theoretical study of pion-nucleus interactions based on distorted-wave and coupled-channels impulse approximation. (September 1975—November 1979) Ph.D., University of Chicago, 1980

Kasra Daneshvar (University of Illinois, Chicago Circle Campus, Chicago, Illinois): Study of fusion reaction mechanisms for several heavy-ion systems. (October 1975—October 1979) Ph.D., University of Illinois, 1979

Alexandra R. Davis (University of Chicago, Chicago, Illinois): Heavy-ion research. (January 1979—)

Bradley W. Filippone (University of Chicago, Chicago, Illinois): Experimental nuclear astrophysics. (June 1979—)

Carl A. Gagliardi (Princeton University, Princeton, New Jersey): Weak interactions in nuclear physics. (July 1977—)

Timothy J. Gay (University of Chicago, Chicago, Illinois): Polarization effects in the beam-foil interaction. (April 1978—)

Suzanne A. Gronemeyer (Washington University, St. Louis, Missouri): Nuclear properties of ^{45}V. (January 1977—September 1979) Ph.D., Washington University, 1979

*Joint appointment with the Fermi National Accelerator Laboratory.

Jonathan E. Hardis (University of Chicago, Chicago, Illinois): Ion-ion and ion-atom collisions. (October 1979—)

Samuel M. Levenson (University of Chicago, Chicago, Illinois): Nuclear physics research. (January 1979—)

Martin J. Murphy (University of Chicago, Chicago, Illinois): Experimental nuclear physics. (January 1976—November 1979) Ph.D., University of Chicago, 1979

Short-Term Visitors (at Argonne less than 4 months during the year)

Larry E. Campbell (Hobart & William Smith Colleges, Geneva, New York): Further development of Mössbauer quantum beats technique; Xe-fluorine compounds intercalated in graphite. (June 1979—August 1979)

Domenico Delli Carpini (Fordham College, Bronx, New York). Undergraduate student. (January 1980—)

Richard W. Chamberlin, Jr. (Illinois Institute of Technology, Chicago, Illinois). Undergraduate student.

Tsewei Chen (Northwestern University, Evanston, Illinois): Nuclear physics. Graduate student.

John W. Clark (Washington University, St. Louis, Missouri): Applications of the variational method and the method of correlated basis functions to problems in nuclear matter theory; comparison with results from other approaches. (August 1979)

Thomas W. Dombeck (University of Maryland, College Park, Maryland): Electric dipole moment of the neutron.

Anita L. Glover (Longwood College, Farmville, Virginia). Undergraduate student. (January 1979—April 1979)

Robert P. Goddard (University of Wisconsin, Madison, Wisconsin): Light ion extension of the DWBA program PTOLEMY.

Gerald Hardie (Western Michigan University, Kalamazoo, Michigan): Studies of $T=\frac{1}{2}$ mirror nuclei in the $f_{7/2}$ shell. (June 1979—July 1979)

Shimon A. Levit (Weizmann Institute of Science, Rehovot, Israel): Nuclear many-body theory. (July 1979—August 1979)

A. Eugene Livingston (University of Notre Dame, Notre Dame, Indiana): Beam-foil spectroscopy of neutral and ionized atoms.

Jeffrey W. Lynn (University of Maryland, College Park, Maryland): Electric dipole moment of the neutron.

George C. Morrison (University of Birmingham, Birmingham, England): Analysis of π^+/π^- scattering on ^{14}N; heavy-ion experiments on tandem. (July 1979—September 1979)

Kenneth J. Moy (Illinois Institute of Technology, Chicago, Illinois): Experimental study of the sputtering yields and the surface damage of TiB_2 coatings under D^+ and He^+ ion bombardment. Graduate student. (May 1979—August 1979)

William O. Perkins (North Carolina State University, Raleigh, North Carolina). Undergraduate student.

Ludwig F. Rohrer (University of Munich, Munich, Germany): Development of control and metering systems for the FN Tandem accelerator. (October 1979—November 1979)

Patrick G. Santangelo (Loyola University, Chicago, Illinois). Undergraduate student. (June 1979—August 1979)

Ralph E. Segel (Northwestern University, Evanston, Illinois): Nuclear physics research.

William D. Teeters (Chicago State University, Chicago, Illinois): Nuclear shell theory.

William C. Trogler (Northwestern University, Evanston, Illinois): Photoelectron spectroscopy of metal cluster complexes.

Bilin P. Tsai (University of Minnesota, Duluth, Minnesota): Laser ionization spectroscopy. (March 1979—May 1979)

John G. Zabolitzky (Ruhr University, Bochum, Germany): Convergence properties of hole-line and coupled-cluster expansions. (July 1979—August 1979)

Paul R. Zschack (Illinois Institute of Technology, Chicago, Illinois). Undergraduate student.

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