ANL-84-24

ANL-84-24

PHYSICS DIVISION ANNUAL REVIEW
1 APRIL 1983 — 31 MARCH 1984

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated by THE UNIVERSITY OF CHICAGO
for the U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A13
Microfiche copy: A01

Distribution Category:
Physics—General
(UC-34)

ANL-84-24

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

PHYSICS DIVISION ANNUAL REVIEW
1 APRIL 1983—31 MARCH 1984

Donald S. Gemmell
Division Director

August 1984

Preceding Annual Reviews

ANL-81-79	1980—1981
ANL-82-74	1981—1982
ANL-83-25	1982—1983

VERIFICATION OF ADDRESS AND CONTINUED INTEREST

In order that we may verify your address on our distribution list, please detach this form, complete the information requested, and return it to the address listed below.

NAME ______________________________

ADDRESS ______________________________

____

____

____

____

____

☐ I wish to continue to receive the Argonne Physics Division Annual Reports

☐ Please remove my name from the distribution list.

Please return to:

Karen Thayer
Physics Division - Bldg. 203
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, Illinois 60439

FOREWORD

The Physics Division Annual Review presents a broad but necessarily incomplete view of the research activities within the Division for the year ending in March 1984.

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

NUCLEAR PHYSICS RESEARCH

Page

Page

ATOMIC AND MOLECULAR PHYSICS RESEARCH

Page

NUCLEAR PHYSICS RESEARCH

Introduction

Research in Nuclear Physics within the Argonne Physics Division is carried out in many of the most active areas of the science. The major nuclear physics facility at Argonne is the superconducting linear accelerator for heavy ions. The research program on this, both in house and outside, represents the largest Argonne commitment to nuclear physics. The superconducting linac is being expanded into a larger facility, ATLAS, whose completion is expected in 1985. Considerable effort over the past year has gone into preparation for ATLAS, not only in terms of the accelerator itself but also in the planning of the experimental area and the various ancillary experimental facilities. The research program, though it has been slowed down by the need to prepare for ATLAS, has made good use of the unique properties of the present linac. Experiments are being carried out on the importance of quasielastic and particularly neutron-transfer reactions as a dominant feature of near-Coulomb-barrier heavy-ion reactions. The studies of nuclear properties at high angular momentum, of heavy-ion fusion reactions, of systematics of fission are all being pursued agressively making good use of the unique properties of the accelerator. The technology of radiofrequency superconductivity as applied to particle acceleration is being developed further. A new type of quarter-wave structure has been constructed out of niobium and the feasibility of accelerating structures for very low-velocity particles is being investigated.

The medium-energy physics program is studying the non-nucleon degrees of freedom of nuclear systems, making use of a variety of national facilities (LAMPF, Bates, etc.). The study of pion absorption on nuclei continues to be a fruitful and interesting program, and has stimulated a great deal of theoretical interest. The Argonne group has continued with its program of tensor polarization measurements of pion and electron scattering from the deuteron. Considerable effort is being devoted to the development of a polarized-gas deuteron target, suitable for use with storage rings. Electron and pion scattering experiments are used to study nuclear structure. Properties of the weak interaction are being addressed by experiments at the Argonne Dynamitron, by participation in a major effort to search for neutrino oscillations at LAMPF, and by high precision studies of the neutron beta decay.

The nuclear theory program is also involved in exploring the connection between nuclei and the subnucleonic degrees of freedom. Work ranges from understanding the pion and delta degrees of freedom to the analysis of the EMC effect in the deep inelastic lepton scattering from nuclei. Questions of heavy-ion reaction theory with particular attention to coupled-channel effects are being investigated. A variety of other questions from variational calculations of many-body systems to nuclear structure are also being pursued.

I. MEDIUM-ENERGY PHYSICS RESEARCH

INTRODUCTION

The goal of medium-energy research in the Argonne Physics Division is to advance our empirical understanding of fundamental particle reactions in nuclei and provide rigorous tests of theoretical descriptions of these processes. As part of that program pion beams at LAMPF and TRIUMF have been used to study pion propagation and absorption in nuclei and as a spectroscopic tool for studying nuclear structure. Recently, two-nucleon coincidence measurements of pion-absorption spectra provided for the first time a direct estimate of the importance of reactions with $T = 1$ nucleon pairs (e.g. p-p or n-n pairs) in describing the dynamics of the absorption process. The other major reaction channel, quasifree scattering, has been delineated in studies of the spectra of inelastically-scattered pions. Inclusive measurements of the pion-charge-exchange reactions have provided new information on the partition of the reaction strength and the isospin dependence of the delta-nucleus optical model. Recent polarization measurements, led by the ANL group, of π scattering by the deuteron, the simplest nuclear system, provide a benchmark for testing various pion-nucleus reaction theories. The results dramatize the limits of present theoretical calculations. The techniques developed in these pion studies provide a powerful tool for fundamental studies of the deuteron using electron scattering. The first experiment to measure tensor polarization in electron scattering has been completed at the Bates Laboratory in collaboration with a group at the Massachusetts Institute of Technology. Nuclear-structure studies exploit the unique features of pions and other medium-energy probes to examine the response of nuclear matter to spin excitations which have a direct bearing on the mean pionic field in the nucleus. Work in the weak-interaction program is focused on the structure of the weak currents and the search for neutrino oscillations at LAMPF. In recent β-decay studies, the importance of pion-exchange currents in pseudo-scalar beta decays was conclusively demonstrated. Also of fundamental importance are particle searches for heavy magnetic monopoles which were begun in 1983 and a search for free quark trapping at cryogenic temperatures completed in 1983.

A large part of the scientific program is centered around the general questions of pion interactions with nuclei--primarily in the Δ(1232) resonance region. Pion absorption plays a major role in any complete description of pion-nucleus reactions. Absorption in ^{3}He provides the best reaction for comparing the relative contribution of $T = 1$ and $T = 0$ nucleon pairs, a point of fundamental importance in a complete theory. Preliminary measurements demonstrate that the $T = 1$ contribution is weak, and a comprehensive series of measurements in progress will provide a complete set of data for the two-nucleon branch and information on the dynamics of three-body absorption.

One of the most stringent tests of our understanding of the pion-nucleus interaction is the study of pion-deuteron scattering. Measurements of the angular and energy dependence of the tensor polarization were completed in 1983. The results do not support previous theoretical work and have spurred more realistic treatment of pion absorption. The techniques used in the pion measurements led to the first experimental measurement of tensor polarization in electron-deuteron elastic scattering, a collaboration with a group at

MIT. This type of experiment is expected to place stringent constraints on the deuteron wave function. Efforts are in progress to develop a polarized gas target which can be used to extend these data to higher momentum transfer through internal-target measurements at the ALADDIN electron storage ring.

The study of properties of nuclear structure with pion scattering is an important aspect of the program. The isospin structure of the π-N interaction and the availability of both π^+ and π^- as projectiles permit the independent determination of neutron and proton transition amplitudes. Nuclear states which are unfavored by other probes can be studied, e.g. isoscalar spin-flip excitations. Current efforts are focused on understanding the quenching of spin-flip strength in high-spin particle-hole states, and include experiments with electrons and protons as well as pions. This work benefits from a close collaboration between experimentalists and theorists in the Physics Division.

The basic properties of weak interactions are being explored in a broad range of activities which include studies of nuclear beta decay performed at the Physics Division Dynamitron, a search for neutrino oscillations under preparation at LAMPF, new high-precision measurements of neutron beta decay in progress at the Institut Laue-Langevin, and research on the electron dipole moment of the neutron. The weak-interaction group has assumed responsibility for the design and construction of the active and passive shield for the LAMPF neutrino experiment (E645). The objective of this measurement is to provide a higher sensitivity to the lepton mixing angle and neutrino mass difference than previous efforts. Studies of low-energy beta decay of ^{16}N and ^{16}C have provided new information on meson-exchange processes and the induced pseudo-scalar coupling strength in nuclei.

A. STUDY OF PION-REACTION MECHANISMS

The purpose of studies of the dynamics of the pion-absorption mechanism and pion scattering is the complete characterization of the interaction of pions in nuclear matter. The (π,NN) experiments on ^3He are crucial for a partial-wave decomposition of the absorption process and can provide fundamental information on the inelasticities of the nucleon-nucleon phase-shift parameters. Further measurements of 3-body absorption modes in ^3He and ^4He will provide the basic structure to interpret the large number of nucleons involved in the absorption process on heavier nuclei. Associated issues in this work deal with questions of pion and nucleon mean-free paths in nuclear matter. Coincidence measurements of quasifree electron scattering are planned to resolve these questions. The relationship between inelastic scattering and absorption has been probed in inclusive scattering measurements where experiments have determined the dominant reaction mode and the dependence of the distribution of reaction strength on the structure of the target. Future coincident measurements will be made of exclusive scattering by ^4He, a target for which microscopic theoretical calcuations of the reaction spectra are in progress. Inclusive measurements of single-charge exchange were completed during 1983. The data provide new information on multistep processes and the isospin dependence of the average Δ-nucleus potential.

a. Study of the 165-MeV Pion Absorption Mechanism in ^3He through the (π^+,2p) and (π^-,pn) Reactions (D. Ashery, D. F. Geesaman, S. M. Levenson,* J. P. Schiffer, G. Stephans, E. Ungricht, B. Zeidman, B. D. Anderson,† G. Das,‡ R. Madey,† R. D. McKeown,§ R. C. Minehart,‡ S. Mukhapadhyay,* E. Piazetsky,‖ R. E. Segel,* C. Smith,‡ J. Watson,† and R. R. Whitney,‡)

In a previous study, it was found that the (π^-,pn) reaction in ^3He and ^4He was strongly suppressed compared with the (π^+,2p) reaction. This result indicates that pion absorption on a J=0, T=1 pair of nucleons is strongly suppressed from that on a J=1, T=0 pair. If pion absorption proceeds dominantly through the Δ-N orbital angular momentum $L_{\Delta N}$ = 0 or 2, then one would expect absorption on the T = 1 nucleon pair to be hindered by conservation of spin and parity. New measurements of the angular dependences of the $^3He(\pi^+,pp)$ and $^3He(\pi^-,pn)$ reactions were carried out to provide more quantitative information on the cross section and on the orbital angular momenta involved. The experiment was performed in the P^3 area at LAMPF with 165-MeV pions incident on a liquid ^3He target. In each coincidence event, one proton was detected in the LAS spectrometer and the coincident proton or

*Northwestern University, Evanston, Illinois.
†Kent State University, Kent, Ohio.
‡University of Virginia, Charlottesville, Virginia.
§California Institute of Technology, Pasadena, California.
‖Los Alamos National Laboratory, Los Alamos, New Mexico.

neutron was detected in two arrays of plastic scintillators, each 40" high by 40" wide. The energy of the particle in the scintillator was determined by the flight time. One scintillator array was positioned at the conjugate angle for two-body absorption while the other provided a measure of three body processes. The angular distribution was determined for proton lab angles of 30, 45, 60, 75, 95 and 120°. These angular distributions are shown in Fig. I-1. Both the π^+ and π^- angular distributions are symmetric about 90°, in contrast to the 65-MeV data where a significant asymmetry was observed for π^- absorption. This indicates that on resonance, there may not be significant interference between isobar and non-isobar contributions to absorption on T = 1 pairs. Information on the three-body absorption ($\pi^+ + {}^3He \rightarrow 3p$) has also been obtained.

b. Study of Low-Energy Pion Absorption in ^3He (A. Altman,* J. Alster,* K. Aniol,† D. Ashery, B. Barnett, D R. Gill,‡ W. Gyles,† R. R. Johnson,† S. M. Levenson,§ J. Lichtenstadt,* M. A. Moinester,* R. Sobiev,‖ R. Tacik, and J. Vincent‡)

The reactions $^3He(\pi^+,pp)$ and $^3He(\pi^-,pn)$ were studied at a pion kinetic energy of T_π = 65 MeV at TRIUMF. The ^3He nucleus is the simplest system in which pion absorption on S = 1, T = 0 and S = 0, T = 1 nucleon pairs can be studied and compared. Previous measurements of pion absorption on the deuteron provided information only on the S = 1, T = 0 case at low density. The present ^3He studies should help better understand the nucleon-nucleon interaction, the role of the Δ in pion absorption, and the mechanisms of pion absorption in heavier nuclei. An article on this work is being submitted for publication.

---

*Tel Aviv University, Israel.
†University of British Columbia, Vancouver, B.C., Canada.
‡TRIUMF, Vancouver, B.C. Canada.
§Northwestern University, Evanston, Illinois
‖University of Toronto, Canada.

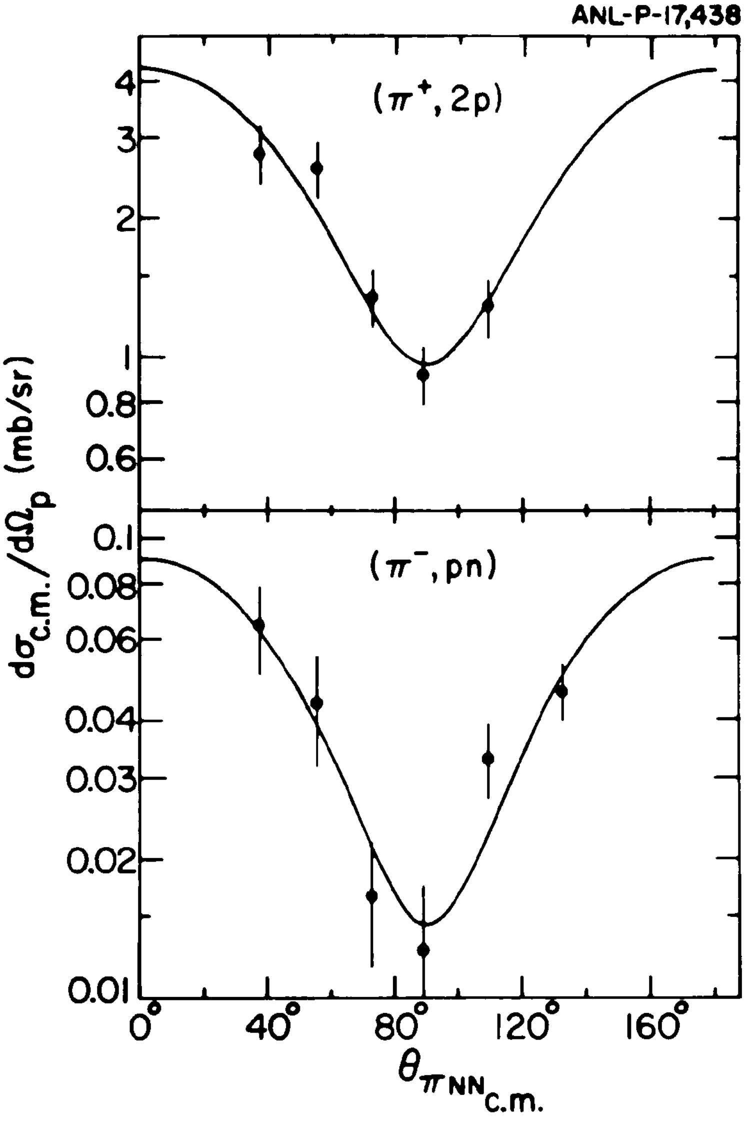

Figure I-1. Angular distributions for $^3He(\pi^{\pm},{}^{pp}_{pn})$ reactions at 165 MeV are shown in the πNN center-of-mass systems. The solid lines are Legendre fits to the data.

c. Inclusive Pion Charge-Exchange Reactions (D. Ashery, H. W. Baer,* J. D. Bowman,* R. Chefetz,† M. D. Cooper,* J. Comuzzi,† A. Erel,‡ D. F. Geesaman, R. J. Holt, H. E. Jackson, M. Leitch,* R. P. Redwine,† R. E. Segel,§ J. R. Specht, K. E. Stephenson, D. R. Tieger,‖ and P. Zupranski§)

The inclusive differential cross sections for $(\pi^{\pm},\pi^{o})$ reactions on targets of ^{12}C, ^{14}C, ^{16}O, ^{18}O, ^{58}Ni, ^{120}Sn and ^{208}Pb were measured at 160 MeV with the LAMPF π^{o} spectrometer. These data are needed to establish the distribution of reaction strength in pion-nucleus reactions as well as to isolate features of the reaction mechanism. The comparison of the data on carbon and oxygen isotopes provides evidence for the isospin dependence of the pion-absorption process. In particular, the (π^{+},π^{o}) spectra have somewhat different shapes from the spectra observed in $(\pi^{+},\pi^{+'})$ reactions. Multiple-step processes appear to be quite important in the charge-exchange spectra.

The A dependence of the charge exchange cross sections are quite different for π^{+} and π^{-} reactions. The cross sections for (π^{+},π^{o}) behave as $A^{0.48}$ or $(N)^{0.45}$. The corresponding power for charged-pion scattering is 0.43. For π^{-}- induced charge exchange, the cross section saturates for $A \sim 100$. This saturation may be due to screening of the protons by valence neutrons and to Pauli blocking of final neutron states in the (π^{-},π^{o}) reaction. The Pauli effects also suppress the forward-angle cross section resulting in substantial deviations in the angular distribution from the free process. A paper reporting the conclusions of this work is in preparation.

---

*Los Alamos National Laboratory, Los Alamos, New Mexico.
†Massachusetts Institute of Technology, Cambridge, Massachusetts.
‡Tel Aviv University, Israel.
§Northwestern University, Evanston, Illinois.
‖Boston University, Boston, Massachusetts.

d. Study of the (π,πp) Reaction and Quasifree Scattering in ^4He
(D. Ashery, D. F. Geesaman, R. J. Holt, H. E. Jackson, J. P. Schiffer, J. R. Specht, B. Zeidman, R. E. Segel,* and P. A. M. Gram†)

The measurement of inelastic pion scattering observed in coincidence with a recoil proton was proposed for a target of ^4He. Angular distributions will be obtained for π^+ energies of 160, 220, and 350 MeV. Emergent pions will be detected in the LAS spectrometer while an array of scintillation counters that span a large solid angle will be used to detect protons.

Data resulting from the coincident observation of pions and recoil protons should provide a clear indication of the validity of the impulse approximation in describing the scattering and of the importance of contributions from higher-order processes. The proposal was approved and is expected to be scheduled soon.

---

*Northwestern University, Evanston, Illinois.

†Los Alamos National Laboratory, Los Alamos, New Mexico.

e. The A Dependence of the (e,e'p) Reaction in the Quasifree Region (D. F. Geesaman, M. C. Green, N. S. Chant,* R. J. Holt, S. M. Levenson,† X. K. Maruyama,‡ P. Roos, R. E. Segel,† J. P. Schiffer, E. Ungricht, C. F. Williamson,§ and B. Zeidman)

A proposal to study the A dependence of the (e,e'p) reaction at $|\vec{q}|$ = 540 MeV/c at the Bates electron accelerator has been approved. From the A dependence of the ratio of (e,e'p) coincidence to (e,e') singles events, the macroscopic attenuation of 140 ± 20 MeV nucleons in nuclei will be deduced. This information on proton propagation in nuclei is essential for the analysis of many processes, including pion absorption and inclusive proton-induced reactions. At the present time, proton-elastic-scattering data support a long mean free path (~5 fm). The electron-knockout reactions appear to be the cleanest technique to provide macroscopic and microscopic measures of this fundamental nuclear parameter property.

---

*National Bureau of Standards, Washington, D.C.
†Northwestern University, Evanston, Illinois.
‡University of Maryland, College Park Maryland.
§Massachusetts Institute of Technology, Cambridge, Massachusetts.

f. Study of the (p,π^-) Reaction Very Close to Threshold
(M. C. Green, J. Brown*, G. T. Emery*, W. W. Jacobs*, T. G. Throwe*, and S. E. Vigdor*)

We intend to study the energy dependence of the differential cross section and analyzing powers of the $^{13}C(p,\pi^-)$ $^{14}O_{gs}$ and $^{48}Ca(p,\pi^-)$ reactions for outgoing pion π energies of 5-20 MeV. The measurements will be performed at the Indiana University Cyclotron Facility. The low spins of the reaction participants in the ^{13}C ground state reaction allow a complete determination of the partial-wave amplitudes in the near-threshold region. Because of the attractive Coulomb potential between the residual nucleus and negative pion, the cross section at the reaction threshold starts at a finite value. This is due to the "sub-threshold" production of pions bound in atomic orbitals to the nucleus. As might be expected the results of our analysis may be extrapolated to threshold where it can be compared to pionic atom data. In contrast, for the ^{48}Ca target, the behavior of the two-particle, one-hole, high-spin, stretched states (previously observed at higher bombarding energies) is of interest in this same threshold region.

*Indiana University Cyclotron Facility, Bloomington, Indiana.

B. NUCLEAR STRUCTURE STUDIES

Because of the unique and differing selectivities of the π-nucleus, e-nucleus, and p-nucleus reactions, medium-energy probes can be used to examine many new features of nuclear structure. Measurements of pion-inelastic scattering utilizing the EPICS system have established a quantitative understanding of the pion-nucleus reaction mechanism. The isospin structure of the pion-nuclear interaction can be used to separate neutron and proton transition amplitudes and makes pion scattering the ideal tool to study isoscalar and isovector spin-flip modes in nuclei. In these experiments a systematic quenching of the isoscalar and isovector spin-flip strength to high-spin particle-hole states has been identified. Complementary data from proton and electron scattering reactions are important in establishing the underlying quenching mechanism. Other experiments have been devoted to a study of the momentum dependence of magnetic form factors in ^{48}Ca and a search for resonant structure in the four-neutron system.

a. Inelastic Scattering of Pions by ^{10}B and ^{11}B (B. Zeidman, D. F. Geesaman, C. Olmer,* G. C. Morrison,† G. R. Burleson,‡ J. S. Greene,‡ C. L. Morris,§ R. L. Boudrie,§ R. E. Segel,‖ L. W. Swenson,¶ G. S. Blanpied,** B. R. Ritchie,** C. Harvey,†† and P. Zupranski‖)

Elastic and inelastic scattering of π^+ and π^- by targets of ^{10}B and ^{11}B was studied at T_π = 162 MeV. Angular distributions between 20° and 90° were measured in 5° steps for π^+ and π^-. In addition, spectra were obtained at 3 angles each at T_π = 130 and 250 MeV, namely angles corresponding to momentum transfers where the differential cross sections for ℓ = 2, 3, and 4 are maximized. For nuclei with T ≠ 0 the isospin dependence, the energy

---

*Indiana University, Bloomington, Indiana.
†University of Birmingham, Birmingham, England.
‡New Mexico State University, Las Cruces, New Mexico.
§Los Alamos National Laboratory, Los Alamos, New Mexico.
‖Northwestern University, Evanston, Illinois.
¶Oregon State University, Corvallis, Oregon.
**University of South Carolina, Columbia, South Carolina.
††University of Texas, Austin, Texas.

dependence, and the angular distributions of the cross sections allow multipole decompositions of mixed electric and magnetic transitions - separately for neutrons and protons. Among the results are evidence for a rotational band built upon $(1p_{3/2}^{-1},1d_{5/2})_{4^-}$ neutron particle-hole configurations. The transition to the $11/2^+$ state at 14.04-MeV excitation is found to be severely quenched. A paper is being prepared for publication.

b. Excitation of 8^-, Particle-Hole States in ^{54}Fe (B. Zeidman, D. F. Geesaman, R. D. Lawson, C. Olmer,* A. D. Bacher,* R. L. Boudrie,† C. L. Morris,† R. A. Lindgren,‡ G. R. Burleson,§ S. J. Greene,§ W. B. Cottingame,§ R. E. Segel,‖ L. W. Swenson,¶ G. C. Morrison** and W. H. Kelly††)

The scattering of π^+ and π^- by ^{54}Fe was studied at T_π = 162 MeV utilizing the EPICS system at LAMPF. Particular interest was placed upon the excitation of 8^- states that result from particle-hole configurations of the form $(1f_{7/2}{}^{-1},1g_{9/2})_{8^-}$. Since ^{54}Fe has a neutron excess, both isoscalar and isovector interactions contribute to excitation of T = 1 states while only the isovector interaction leads to T = 2 states. As a result, different spectra are obtained from π^+ and π^- scattering. The data were compared to theoretical nuclear structure predictions and significant deviations from expectations are observed. Reasonable agreement can be obtained between the experimental results and theoretical calculations if the isoscalar contributions are quenched by a factor ~2 relative to isovector contributions. Summation of the experimental isoscalar and isovector strengths for the observed states indicates that the total isoscalar spin-flip strength is quenched by about a factor of three relative to the isovector strength. As seen in Fig. I-2, this greather quenching continues a trend observed in lighter nuclei; ^{54}Fe is the heaviest nucleus for which such an isospin decomposition has been performed. These results are being prepared for publication.

---

*Indiana University, Bloomington, Indiana.
†Los Alamos National Laboratory, Los Alamos, New Mexico.
‡University of Massachusetts, Amherst, Massachusetts.
§New Mexico State University, Las Cruces, New Mexico.
‖Northwestern University, Evanston, Illinois.
¶Oregon State University, Corvallis, Oregon.
**University of Birmingham, Birmingham, England
††Montana State University, Bozeman, Montana.

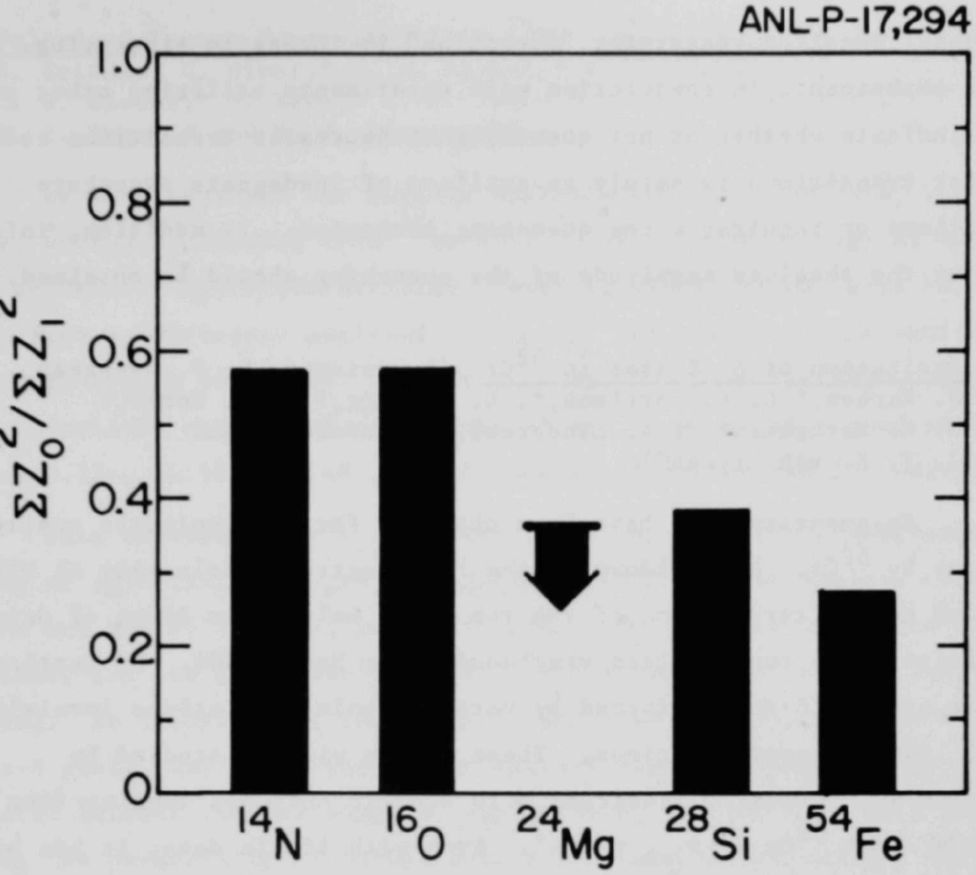

Figure I-2. Ratio of the summed isoscalar strength, ΣZ_0^2, to the summed isovector strength, ΣZ_1^2, for ^{14}N, ^{16}O, ^{24}Mg (upper limit), ^{28}Si and ^{54}Fe.

c. Isoscalar Quenching in the Excitation of 8^- States in ^{52}Cr

(D. F. Geesaman, B. Zeidman, G. C. Morrison,* R. L. Boudrie,† C. L. Morris,† G. R. Burleson,‡ S. J. Greene,‡ and L. W. Swenson§)

The EPICS system at LAMPF has been used in an investigation of the properties of 8^- states in ^{52}Cr excited by the scattering of 162-MeV π^+ and π^-. Previous results for pion scattering by ^{54}Fe show that stretched transitions to 8^- states with configurations $(f_{7/2}^{-1}\ g_{9/2})_{8^-}$ are observable with reasonable cross sections. The experiment is directed toward answering a

*University of Birmingham, Birmingham, England.
†Los Alamos National Laboratory, Los Alamos, New Mexico.
‡New Mexico State University, Las Cruces, New Mexico.
§Oregon State University, Corvallis, Oregon.

fundamental question concerning "quenching" in inelastic scattering. The present experiment, in conjunction with experiments utilizing other probes, should indicate whether or not quenching of isoscalar transitions relative to isovector transitions is merely an artifact of inadequate structure calculations or requires a new quenching mechanism. In addition, information regarding the absolute magnitude of the quenching should be obtained.

d. Excitation of 8^- States in ^{52}Cr (B. Zeidman, D. F. Geesaman, O. Karbon,* G. C. Morrison,*, L. W. Fagg,† D. I. Sober,† X. K. Maruyama,‡ R. A. Lindgren§, H. deVries,‖ and J. F. K. van Hienen¶)

Fragmentary data have been obtained for the inelastic scattering of electrons by ^{52}Cr. A breakdown of the MEA electron accelerator at NIKHEF, Amsterdam caused termination of the run after only a few hours of data acquisition. The run has been rescheduled for March 1984. Of particular interest are the 8-states formed by particle-hole excitations involving $(1g_{9/2}, 1f^{-1}_{7/2})_{8^-}$ configurations. These states will be studied by inelastically scattering electrons with kinetic energies ranging from 140 MeV to 260 MeV from ^{52}Cr at $\theta_{lab} = 154°$. Even with little data, it has been possible to identify the T=3, 8^- state at an excitation energy of ~15.4 MeV. Several other 8^- candidates are also seen, but considerably more data are required for positive identification. These data are needed for a study of the origins of quenching in isovector and isoscalar transitions.

---

*University of Birmingham, Birmingham, England.
†Catholic University, Washington, D.C.
‡National Bureau of Standards, Gaithersburg, Maryland.
§University of Massachusetts, Amherst, Massachusetts.
‖NIKHEF, Amsterdam.
¶Free University, Amsterdam.

e. Polarized Proton Scattering from ^{26}Mg (D. F. Geesaman, B. Zeidman, C. Olmer,* A. D. Bacher,* G. T. Emery,* C. W. Glover,* H. Nann,* W. P. Jones,* S. Y. van der Werf,† R. E. Segel,‡ and R. A. Lindgren§)

We have measured the angular distributions and analyzing powers for polarized proton scattering from ^{26}Mg at 135-MeV incident energy at the Indiana University Cyclotron Facility. Angular distributions were measured in 5° steps from a laboratory angle of 10° to 60° for states in the excitation energy range from 0 to 20 MeV. Five 6^- states have been identified based on the characteristic angular distributions of the cross sections and analyzing powers at 9.17-, 11.98-, 12.48-, 12.85- and 18.05-MeV excitation energy.

This experiment is a continuation of our efforts to understand the quenching of spin-flip strength in high-spin particle-hole states. The phenomena are now well established throughout the periodic table for $\Delta T = 1$ transitions, and are also observed for $\Delta T = 0$ transitions in pion and proton scattering. By studying the inelastic strength as a function of deformation in the s-d shell, and as a function of angular momentum transfer, we hope to distinguish between several proposed explanations for the quenching mechanism, including the possibility of isobar-hole admixtures in the nuclear wave functions.

---

*Indiana University, Bloomington, Indiana.
†K.V.I., Groningen, The Netherlands.
‡Northwestern University, Evanston, Illinois.
§University of Massachusetts, Amherst, Massachusetts.

f. Transverse Electron Scattering by ^{26}Mg (A. D. Bacher,* D. F. Geesaman, R. S. Hicks,† R. L. Huffman,† R. A. Lindgren,† X. K. Maruyama,‡ C. Olmer,* M. A. Plum† and B. H. Wildenthal§)

The inelastic scattering of electrons by ^{26}Mg was studied using the 180° inelastic-electron-scattering facility at the Bates Linear Accelerator Laboratory. Preliminary measurements were made at incident energies of 140 and 192 MeV where the momentum transfer corresponds to the peak of the

---

*Indiana University, Bloomington, Indiana.
†University of Massachusetts, Amherst, Massachusetts.
‡National Bureau of Standards, Washington, D.C.
§Michigan State University, East Lansing, Michigan.

transverse form factors for E4 and M6 multipolarities, respectively. Five 6^- states were tentatively identified including the 6^-, T = 2 state at 18-MeV excitation. These data along with that of the previous (p,p') measurement will permit the determination of the isoscalar and isovector spin-flip strengths for each 6^- state. Final data for this experiment were obtained in October 1983 and the analysis is still in progress.

g. Inelastic Scattering of p + ^{48}Ca at 160 MeV (K. E. Rehm, R. E. Segel,* P. Kienle,† D. W. Miller,‡ and J. R. Comfort§)

The analysis of the data for inelastic scattering of $\vec{p}$ on ^{48}Ca obtained in an experiment at IUCF has been completed. DWIA calculations assuming simple particle-hole excitations describe the angular distributions at small momentum transfers. The analyzing powers seem to be very sensitive to the structure of the wave functions. An 8^- state at E_x = 9.309 MeV with ≃30% of the strength of a $(f_{7/2}{}^{-1}\ g_{9/2})$ transition has been identified. A paper with the results has been submitted for publication. A proposal to study this reaction at higher p-energies (E ≃400 MeV) at LANL was approved.

*Northwestern University, Evanston, Illinois.
†Technical University, Munich, W. Germany.
‡Indiana University Cyclotron Facility, Bloomington, Indiana.
§University of Arizona, Tucson, Arizona.

h. Study of the ^{4}He($\pi^-\pi^+$) Reaction at Small Angles (D. F. Geesaman, R. J. Holt, R. D. McKeown,* C. L. Morris,† J. R. Specht, K. E. Stephenson, J. Ungar,* and B. Zeidman)

The momentum spectrum for double charge exchange of π^- on ^{4}He was measured at 0° and T_{π^-} = 165 MeV. A 1σ upper limit of 22 nb/sr was set on the cross section for transitions leading to bound tetraneutrons. The limit is almost two orders of magnitude lower than previous determinations. The experimental spectrum for unbound final states is shown in Fig. I-3. The curves in this figure represent relativistic phase-space calculations for four neutrons including final-state interactions (solid), final-state interactions in one of the neutron pairs (dot-dashed) and final-state interactions in both

*California Institute of Technology, Pasadena, California.
†Los Alamos National Laboratory, Los Alamos, New Mexico.

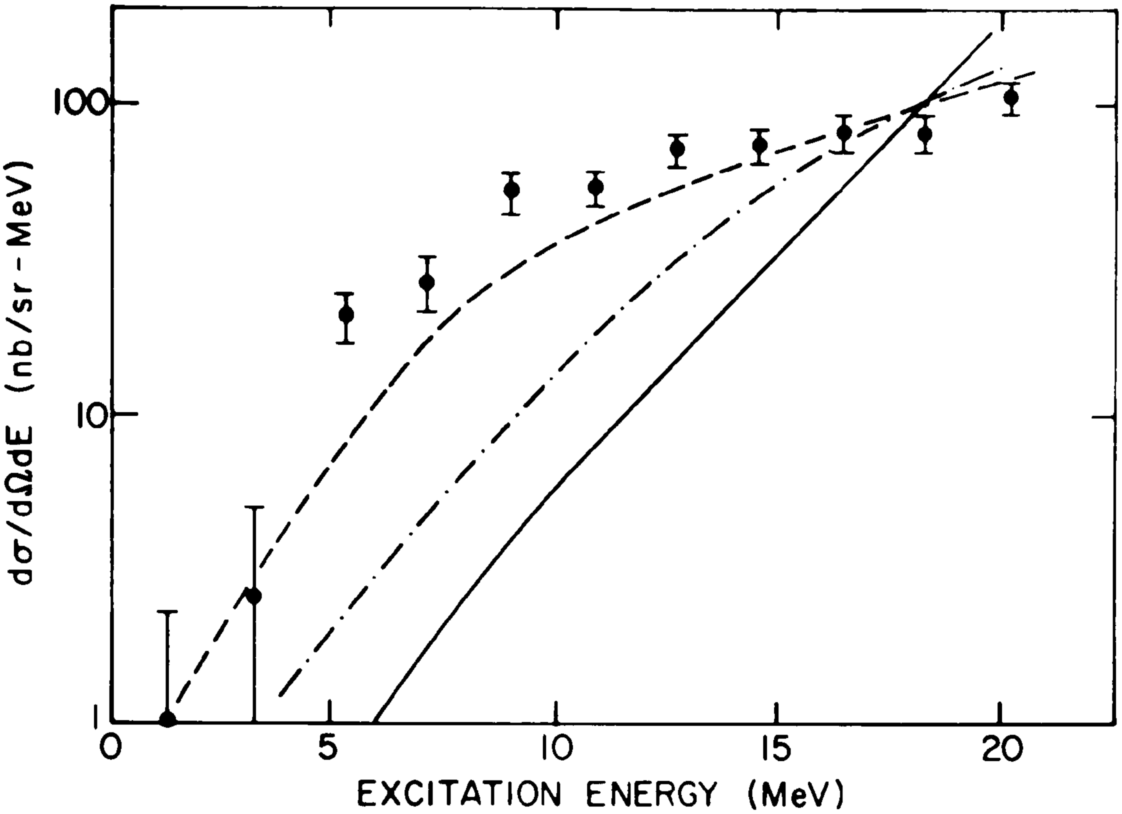

Figure I-3. The experimental results are plotted against the excitation of the final four-neutron states. The solid curve corresponds to the pure four-neutron phase space, while the dot-dashed and dashed curves are the four-neutron phase-space curves with singlet final-state interactions in, respectively, one and both of the final-state neutron pairs.

neutron pairs (dashed). The large effects of the final-state interactions indicate that a correct treatment of the four-neutron final state is essential in any calculations of these cross sections. A paper discussing these results has been submitted for publication.

i. High-Spin, Two-particle, One-hole, "Stretched" States Excited by Proton Induced Negative Pion Production in Nuclei (M. C. Green, J. Brown*, W. W. Jacobs*, P. L. Jolivette†, T. G. Throwe*, S. E. Vigdor*, and T. E. Ward*)

An unexpected feature of proton-induced negative-pion production on nuclei, (p,π^-) is the selective excitation of two-particle (protons), one-hole (neutron), high-spin stretched (and nearly-stretched) states at low excitation in the residual nuclei. These states have been found to be most strongly excited in target nuclei where the high-spin $j_>$ neutron orbital is filled and the corresponding $j_>$ proton orbital is empty. This and a number of systematics can be understood qualitatively in terms of a two-nucleon reaction mechanism for (p,π^-), where the underlying process in the nucleus is assumed to be $p + n \rightarrow p + p + \pi^-$. The incoming proton interacts with a neutron in the highest spin orbital of the target nucleus producing a negative pion and leaving a neutron hole. The two residual protons from this reaction couple with the neutron hole to maximum or nearly maximum spin to accomodate the high momentum transfer (therefore high angular-momentum transfer) inherent in pion production reactions to discrete final states. We have observed the cross section and analyzing-power distributions of these 2p-1h configurations from targets of oxygen, calcium, and (this past fall) strontium. Each target isotope was chosen to have the highest filled neutron orbital correspond to an empty proton orbital. Respectively, the configurations for the observed states are $(1d_{5/2})^3$, $(1f_{7/2})^3$, and $1g_{9/2})^3$ having spins as large as $13/2^+$, $19/2^-$, and $25/2^+$. Remarkably, the analyzing-power distributions of the highest spin states in all three nuclei were found to be quite similar, a qualitative observation which awaits explanation. In the next year we plan to continue our studies to heavier nuclei; in particular, to the appropriate samarium and lead isotopes where we hope to observe states based on the $(1h_{11/2})^3$ and $1i_{13/2})^3$ 2p-1h configurations, respectively. The high-spin stretched states for these two cases would be $31/2^-$ and $37/2^+$.

---

*Indiana University Cyclotron Facility, Bloomington, Indiana.
†Hope College, Holland, Michigan.

C. TWO-NUCLEON PHYSICS WITH PIONS AND ELECTRONS

After years of effort, an understanding of the N-N interaction remains a central concern for nuclear physics. Measurements of polarization observables in pion and electron reactions on the deuteron provide information on the pion absorption mechanism and on isoscalar exchange currents. The data on the angular distribution of the tensor polarization in π-d scattering cannot be explained by any current theory. During 1982 the tensor polarization t_{20} in e-d elastic scattering was measured for the first time. Since the momentum transfer range (1.7--2 fm^{-1}) of this measurement is comparable with that of the tensor polarization measurements in π-d scattering and since good agreement was found between the results and calculations which employ reasonable deuteron wave functions, this confirms the suspicion that the discrepancies between the experiment and calculations in π-d scattering arise from an incomplete knowledge of the inelastic channel (πd- → NN) rather than of the deuteron wave function.

Studies to continue these measurements at higher momentum transfer using an electron storage ring are underway. In other experiments, low-energy photodisintegration measurements revealed problems with the conventional nucleon-meson descriptions of the deuteron in predicting the neutron polarization in the $d(\gamma,\vec{n})$ reaction.

a. Tensor Polarization in π-d Elastic Scattering and Pion Absorption (E. Ungricht, W. S. Freeman, D. F. Geesaman, R. J. Holt, J. R. Specht, B. Zeidman, E. J. Stephenson,*, J. D. Moses,† M. Farkhondeh,‡ S. Gilad,§ and R. P. Redwine§

The pion absorption mechanism in nuclei has emerged as a major issue in medium-energy physics during the past few years. Although many studies involving the πd→NN reaction have been performed, the absorption process has not been explained adequately and the effect of pion absorption on the elastic amplitudes is poorly understood. In order to further investigate the effect of absorption on the elastic channel, recent theoretical calculations[1] have focused on the P_{11} π-N amplitude since this amplitude is necessary for absorption. These calculations indicate that tensor polarization t^{20}_{lab} of the

*Indiana University Cyclotron Facility, Bloomington, IN.
†Los Alamos National Laboratory, Los Alamos, NM.
‡ Graduate Student, Massachusetts Inst. of Technology, Cambridge, MA.
§Massachusetts Institute of Technology, Cambridge, MA.
[1]B. Blankleider and I. R. Afnan, Phys. Rev. C 24, 1572 (1981); M. Betz and T.-S. H. Lee, Phys. Rev. C 23, 375 (1981); C. Fayard, G. H. Lamot, and T. Mizutani, Phys. Rev. Lett. 45, 524 (1980); A. S. Rinat and Y. Starkand, Nucl. Phys. A397, 381 (1983); T. Mizutani, C. Fayard, G. H. Lamot,and S. Nahabetian, Phys. Rev. C 24, 2633 (1981).

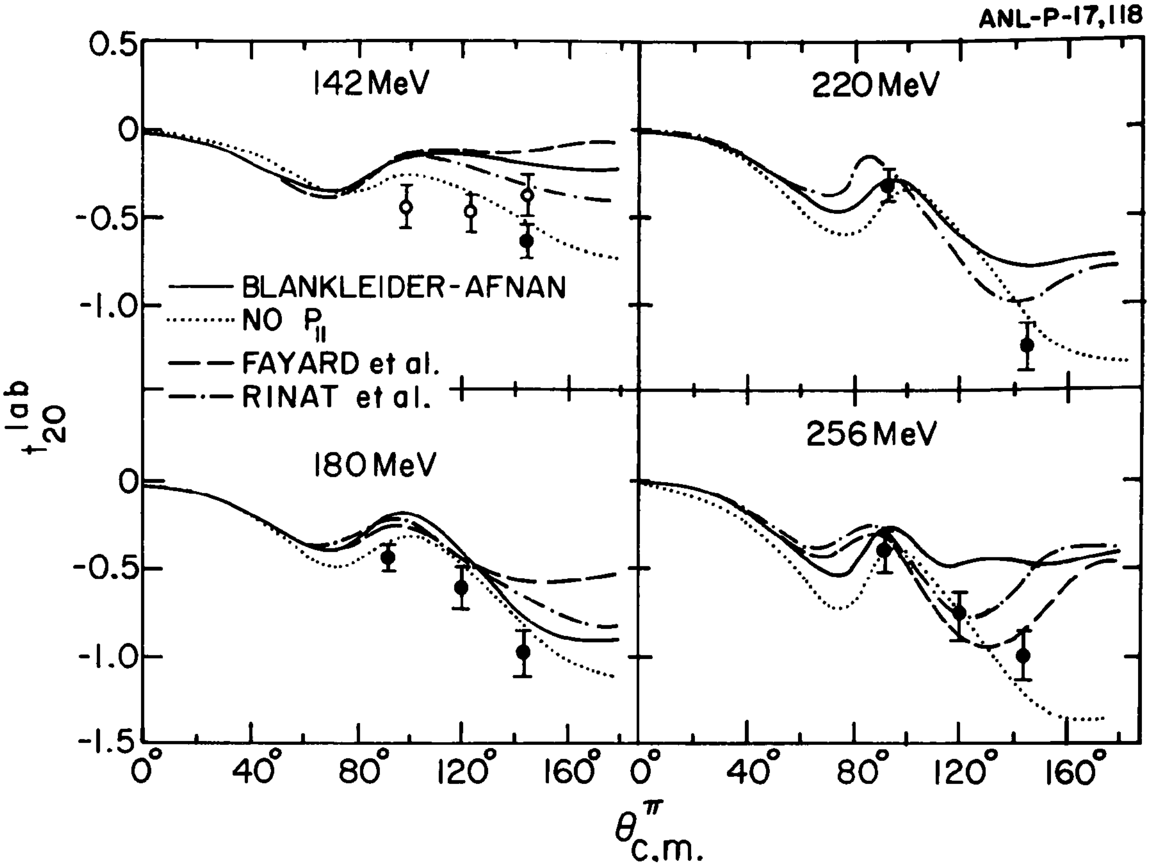

Figure I-4. Present measurements of t_{20}^{lab} are indicated by the darkened points while the previous measurements of Ref. 1 are represented by the open circles. The results agree best with the calculations which contain no P_{11} π-N amplitude, the dotted curve.

recoil deuteron from π-d elastic scattering is sensitive to the exact composition of the P_{11} π-N amplitude.

As a test of these calculations, we have measured the angular dependence of t_{20}^{lab} of recoiling deuterons in π-d scattering in the incident pion energy region of 134 to 256 MeV. The results are shown in Fig. I-4 and agree most favorably with the calculations in which the P_{11} π-N amplitude has been removed althogether, the dotted curves. This agreement is consistent with a small effect of pion absorption on the elastic channel. No apparent evidence for dibaryon resonances is seen in the data and is consistent also with a small coupling of the absorption channel to the elastic channel.

---

[1]R. J. Holt, J. R. Specht, K. Stephenson, B. Zeidman, J. S. Frank, M. J. Leitch, J. D. Moses, E. J. Stephenson, and R. M. Laszewski, Phys. Rev. Lett. 47, 472 (1981).

b. Measurement of the Tensor Polarization in Electron-Deuteron Elastic Scattering

(M. E. Schulze,* D. Beck,*, M. Farkhondeh,* S. Gilad,† R. Goloskie,‡ R. J. Holt, S. Kowalski,† R. M. Laszewski,§ M. J. Leitch,‖ J. D. Moses,¶ R. P. Redwine,† D. P. Saylor,‡ J. R. Specht, E. J. Stephenson,** K. Stephenson,†† W. Turchinetz,† and B. Zeidman

The tensor polarization in e-d elastic scattering is dominated by the charge and quadrupole form factors of the deuteron, and consequently, it is sensitive to the tensor part of the deuteron wave function and at high momentum transfer the short-range part of the wave function. The deuteron tensor polarimeter that was developed[1] in order to measure t_{20} in π-d scattering was employed at Bates in order to measure the polarization. The results shown in Fig. I-5 indicate that the data are in good agreement with theoretical calculations[2] that use reasonable deuteron wave functions. The tensor polarization was measured for two values of momentum transfer: q = 1.74 and 2.03 fm^{-1}. In addition, the good agreement between the present results for e-d scattering and the calculations at low values of momentum transfer provides additional confidence in the experiment method. It is clear from the curves in Fig. I-5 that the measurements must be extended to higher values of momentum transfer and be of higher accuracy in order to test the available model.

---

*Graduate Student, Massachusetts Inst. of Technology, Cambridge, MA.
†Massachusetts Institute of Technology, Cambridge, MA.
‡Worcester Polytechnic Institute, Worcester, MA.
§University of Illinois, Urbana, IL.
‖TRIUMF, Vancouver, British Columbia, Canada.
¶Los Alamos National Laboratory, Los Alamos, NM.
**Indiana University Cyclotron Facility, Bloomington, IN.
††EMR Photoelectric, Princeton, NJ.

[1]R. J. Holt, J. R. Specht, K. Stephenson, B. Zeidman, J. S. Frank, M. J. Leitch, J. D. Moses, E. J. Stephenson, and R. M. Laszewski, Phys. Rev. Lett. 47, 472 (1981).

[2]M. I. Haftel, L. Mathelitsch, and H. F. K. Zingl, Phys. Rev. C 22, 1285 (1980); M. E. Schultz et al., Phys. Rev. Lett. 52, 597 (1984)

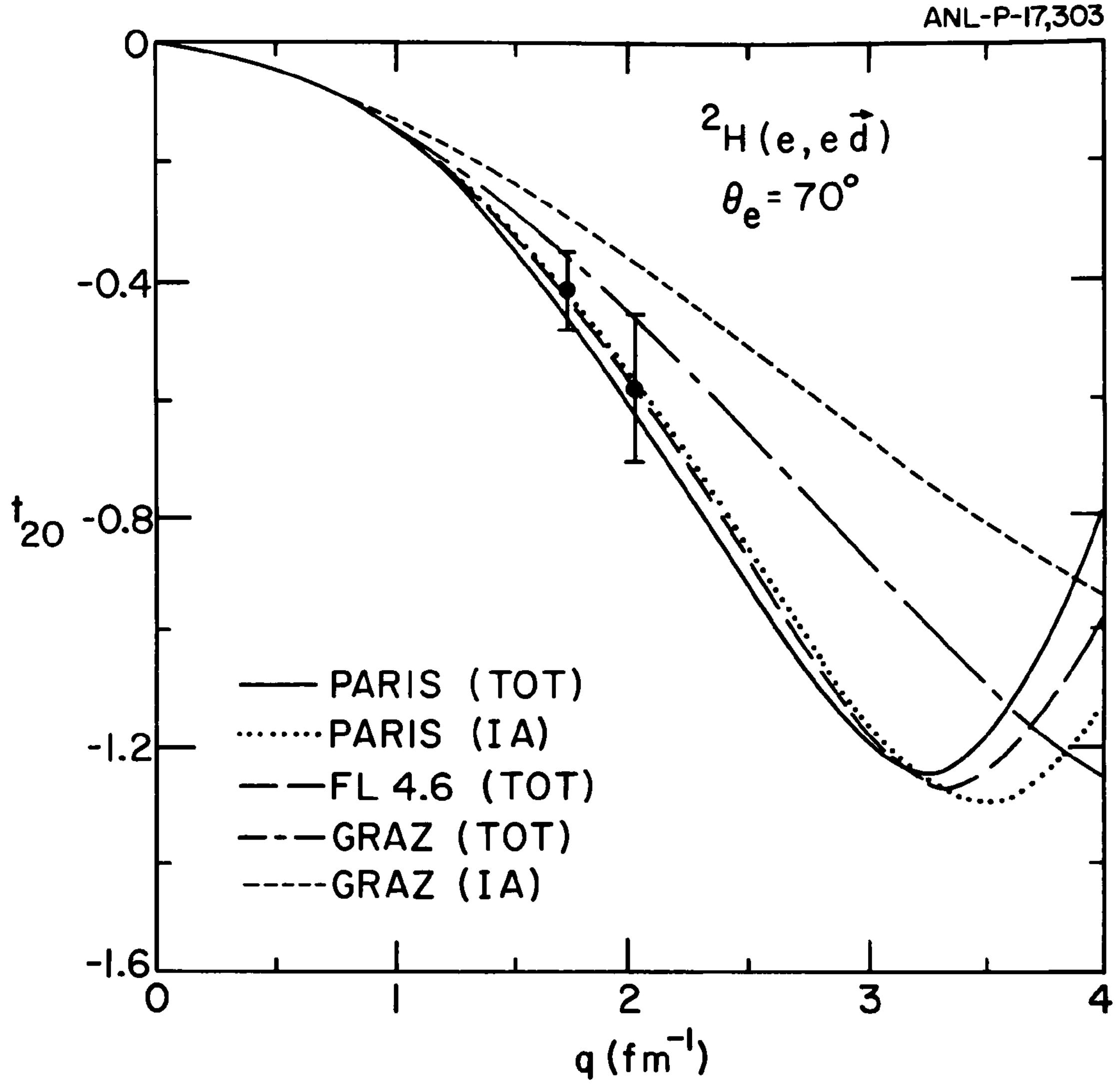

Figure I-5. The two data points indicate the present results. The curves represent predictions of different potential models: Paris, TOT, (____); Paris, IA, (·······); FL4.6, TOT, (___ ___); Graz, TOT, (____ _ ___); Graz, IA, (-------).

c. Feasibility Study of Electron-Scattering Experiments with a Tensor-Polarized Deuterium Target in an Electron Storage Ring

(R. J. Holt, D. F. Geesaman, L. S. Goodman, M. Green, R. Kowalczyk, J. Napolitano, M. Peshkin, E. Ungricht, L. Young, and B. Zeidman)

(a) Electron Ring Tests

This study is centered around the Aladdin storage ring at Wisconsin. This ring is expected to be operational in 1984 and is expected to produce a 1-GeV electron beam with a circulating current of $\gtrsim$100mA. In an experiment involving internal targets it will be necessary to localize the target and to provide differential vacuum pumping. A movable baffle has been designed and constructed for the ring. This baffle will be employed in order to study the radiation background, transverse "tails" associated with the beam and the interaction of the beam in the presence of a baffle as soon as Aladdin becomes operational.

(b) Tensor-Polarized Deuterium Target Development

A prototype of a polarized atomic-beam target which would be suitable for use in storage rings is under construction in order to test a novel scheme for producing a high flux of polarized deuterium nuclei. The method makes use of optically-pumped polarized alkali atoms which transfer polarization to deuterium atoms by spin-exchange interactions. Polarization of the deuterium nuclei will be measured by utilizing the $^3He(d,p)^4He$ reaction which has a high tensor analyzing power and cross section at low energy. Thus far, in a bench test we have achieved 10 mW of laser power which contributes to the spin-exchange process to deuterium. This amount of light absorption is equivalent to an atomic beam of deuterium of ~10^{16} atoms/s, although the polarization of the resultant beam was not measured in this test.

D. WEAK INTERACTIONS

A goal of the weak-interaction program is to determine the structure of weak currents, and to use weak interactions as a probe of hadronic currents. A search for neutrino oscillations at LAMPF addresses two central issues in gauge theories of weak interactions, the mass and the flavor purity of neutrinos. Argonne has assumed a major responsibility in the construction of a large and sophisticated neutrino detector for this experiment. Low-energy source and accelerator-based experiments provide tests of the conserved-vector-current hypothesis, the existence of second-class currents, and precision measurements of g_A for nucleons. The importance of pion-exchange currents in pseudo-scalar beta decays has been conclusively demonstrated in studies of the ^{16}N, $J^\pi=0^-$ 120-keV level to the ^{16}O $J^\pi=0^+$ ground-state beta decay.

a. Neutrino Oscillations at LAMPF (J. Donohue,* S. J. Freedman, G. T. Garvey, M. Greene, R. Imlay,§ M. Kroupa,‖ K. Lesko, T. Y. Ling,¶ R. D. McKeown,** W. Metcalf,§ B. Musgrave,‡ J. Napolitano, T. Romanowski,¶ and M. Timko¶)

Over the past year improvements have been designed into the active and passive shield for the LAMPF Neutrino Oscillation experiment (E645). The design and construction of the shield is ANL's responsibility in this collaborative effort. The design of the active shield is a result of last years experience on prototyping a tank of liquid scintillator. We have studied further the possible sources of neutral backgrounds and have closely followed the results coming from E225 at LAMPF. As a result of these inputs, the overburden is being increased to 2500 g/cm^2 and the inner photon shield has been increased from 17.8 cm of Fe to 5.1 cm of Fe plus 12.7 cm of Pb. This subsitution of Pb for Fe makes the shield 5 x 10^3 times more effective. The design of the shield plus the cart carrying the detector is now complete and is being let out for bid. Construction is to start in late spring following completion of the tunnel at the LAMPF beam stop. Our present estimates for the background fluxes incident on the detector are:

---

*Los Alamos National Laboratory, Los Alamos, New Mexico.
†Texas A. & M University, College Station, Texas.
‡High Energy Physics Division, ANL.
§Louisiana State University, Baton Rouge, Louisiana.
‖Thesis Student, University of Chicago, Chicago, Illinois.
¶Ohio State University, Columbus, Ohio.
**California Institute of Technology, Pasadena, California.

1. muons which stop in the detector - $< 6.5 \times 10^{-2}$/LAMPF Day (LD)
2. cosmic ray neutrons, $E_n > 65$ MeV - 4.5/LD
3. photons from $\mu + N \rightarrow \mu' + \gamma + N$,
   $e + N \rightarrow e + \gamma + N$ - 2.2×10^{-3}/LD
   $E_\gamma > 30$ MeV
4. neutrons from $\mu^- + N \rightarrow n + x$ - 29/LD
   $30 < E_n < 100$ MeV

All of these fluxes are consistent with a goal of less than 10^{-1} events/LD of background simulating $\tilde{\nu}_e$ events in the detector. The process we will first search for is $\tilde{\nu}_\mu \rightarrow \tilde{\nu}_e$. The $\tilde{\nu}_e$ is detected via the $\tilde{\nu}_e + p \rightarrow n + e^+$ reaction on the hydrogen in our 15 tons of scintillator. If all $\tilde{\nu}_\mu$ were to oscillate into $\tilde{\nu}_e$ we would have 47 events $(LD)^{-1}$. Assuming we realize a background level of 10^{-1} LD^{-1} the following limits can be set, for $\Delta m^2 >$ lev^2, $\sin^2 2\theta < 1.7 \times 10^{-3}$ and for $\sin^2 2\theta = 1$, $\Delta^2 m < 2 \times 10^{-2}$ eV^2.

b. Beta Decay of Polarized Nuclei and the Decay Asymmetry of ^{8}Li
(R. Bigelow,* S. J. Freedman, G. Masson,* J. Napolitano, and P. Quin*)

Using the FN Tandem facility at the University of Wisconsin-Madison and the accompanying polarized ion source, we have begun a program of studying the weak interaction via the beta decay of polarized nuclei. Such a study yields information on the validity of CVC, the existence of second-class currents, and the magnitude of certain nuclear matrix elements.

We are presently studying the beta decay of polarized ^{8}Li, produced with a polarized deuteron beam on a cold target of ^{7}Li metal kept in a weak holding field. The asymmetry between up and down polarization states is detected by two electron detector telescopes. Total electron energy is measured with large plastic scintillators. A beta energy spectrum and up/down asymmetry are shown in Fig. I-6. The disappearance of the asymmetry at low energy is due to background from (unpolarized) F^{17} decay. This background is not present unless the target is cold indicating that it originates from a thin layer of ice forming on the target allowing $^{16}O(d,n)^{17}F$. We intend to alleviate this background by improving the vacuum and running at a beam energy low enough to render the $^{16}O(d,n)$ reaction negligible.

*University of Wisconsin, Madison, Wisconsin.

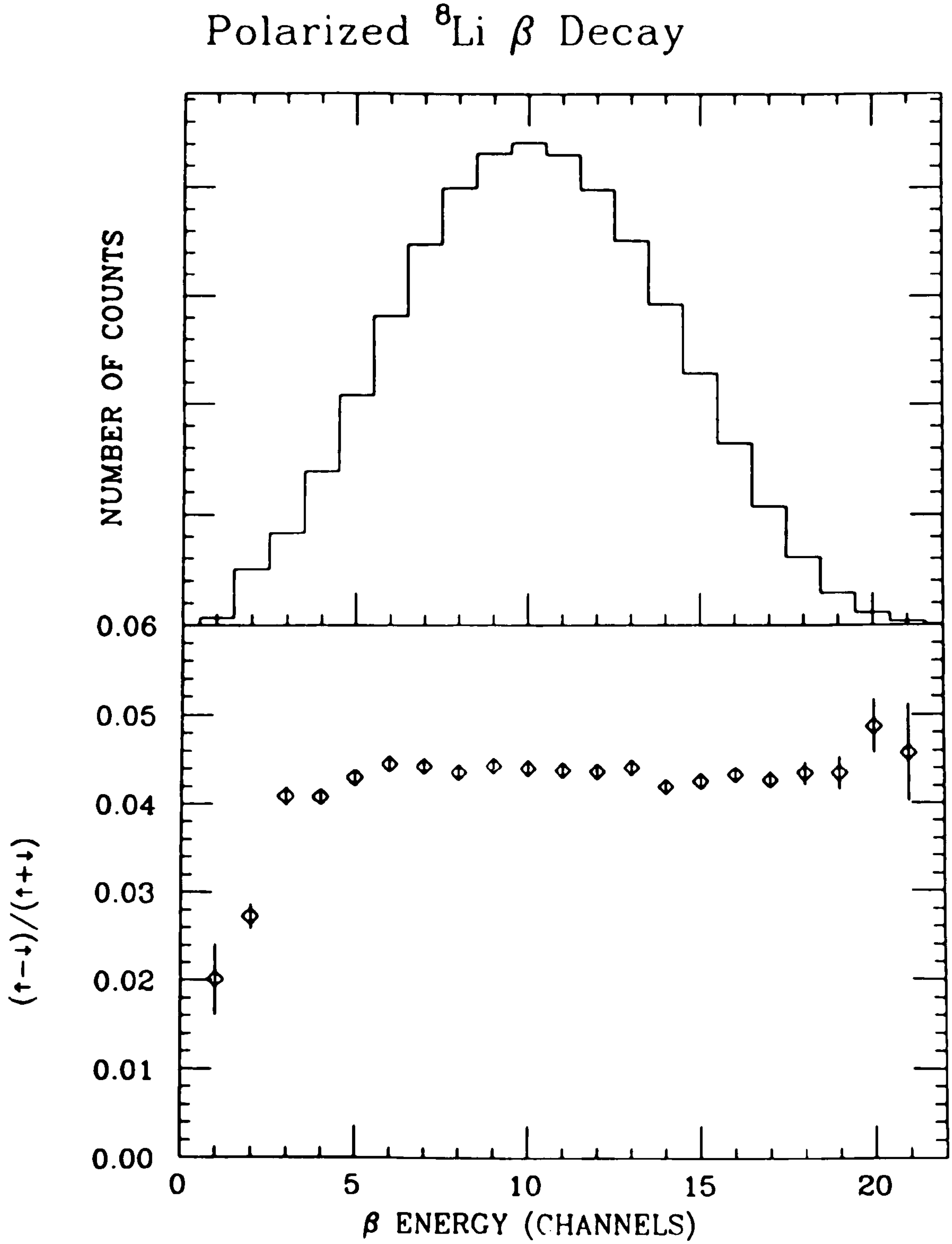

Figure I-6. Energy spectrum and asymmetry for polarized ^{8}Li beta decay.

The need for an accurate energy calibration is also evident. We have tested a calibration procedure based on measuring the endpoints of convenient beta spectra at the Physics Division Dynamitron. A sample calibration using this procedure is shown in Fig. I-7. The results are very encouraging indicating that this procedure provides a sufficiently accurate energy determination.

We are proceeding to update the electronics so that we may withstand higher rates. Our next run will utilize the new University of Wisconsin VAX-11/750-based data-acquisition system. We are also preparing to perform several calibration runs using beta spectra from nuclei with well-defined endpoints.

c. $0^+ \rightarrow 0^-$ Beta Decay of ^{16}C Ground State (C. A. Gagliardi, G. T. Garvey, N. Jarmie,* and R. G. H. Robertson*)

As part of the effort to establish the role of virtual pions in nuclei we have measured the beta decay of the ^{16}C ground state to the 0^-, 120-keV level of ^{16}N. These pseudoscalar matrix elements are known to be greatly affected by pion exchange currents and further the transition matrix elements are very similar to those required to produce $\Delta T = 1$ parity mixing in hadronic systems. This experiment represents the first time that the 0^- branch has been observed in the decay of ^{16}C. The measurement was carried out at the LANL Tandem Van de Graaff, where ^{16}C was produced via the $^{14}C(t,p)^{16}C$ reaction at $E_t = 6.0$ MeV. The use of both a radioactive beam and target allowed the preparation of a much cleaner and stronger ^{16}C source than had heretofore been possible. The prominent decay modes of the ^{16}C ground state are to $J^\pi = 1^+$ neutron unstable states in ^{16}N. We detected the neutrons with a stiblene crystal, the betas in a thin (0.8 mm) plastic scintillator and photons in a 12.5 cm^3 Ge(Li) detector. The absolute efficiency of the Ge(Li) was fixed with calibrated sources while the beta-counter efficiency was determined at ANL using $\beta - \gamma$ coincidences in the $^{20}F \rightarrow {}^{20}Ne$ decay. Our results for the ^{16}C decays are a branching ratio of $6.8^{+0.9}_{-1.1} \times 10^{-3}$ for the decay to the 0^- state and a limit of $<10^{-3}$ for the branch to the 1^- state.

*Los Alamos National Laboratory, Los Alamos, New Mexico.

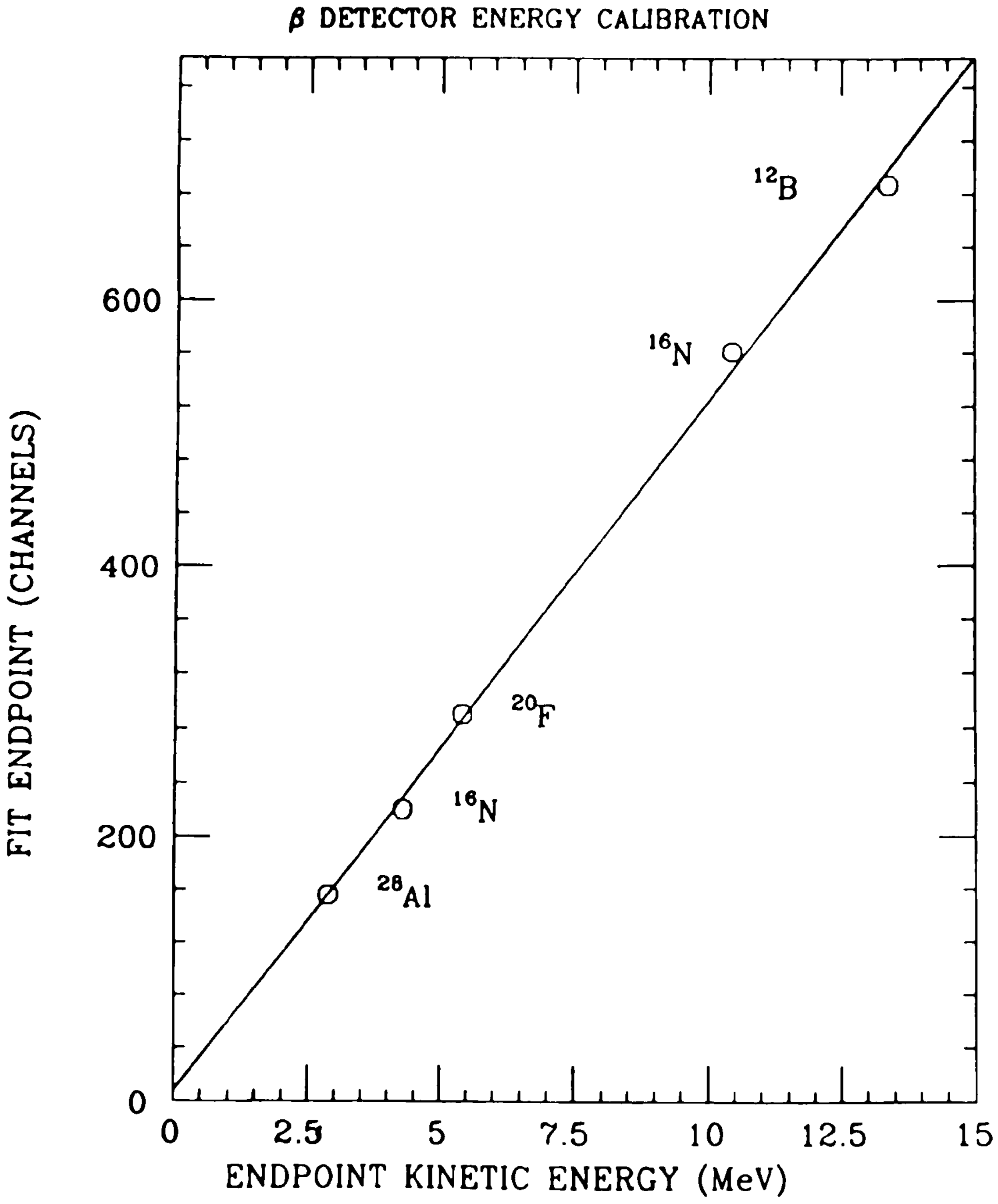

Figure I-7. A sample energy calibration of the beta detector based on endpoints of various beta-decay spectra.

As this $0^+ \rightarrow 0^-$ decay depends principally on $2S_{1/2} \rightarrow 1P_{1/2}$ transitions the rate depends on the amount of the $(2S^2_{1/2})$ component in the ^{16}C ground state. Using an estimate of this component by D. Kurath and our earlier value for the $^{16}N(0^-) \rightarrow {}^{16}O$ ground-state decay rate, we predict a value of the $0^+ \rightarrow 0^-$ branch that is 2.5 times what we observed. A proper calculation of the nuclear structure must be done to determine if we have achieved a quantitative characterization of these pseudoscalar transitions.

d. The Branching Ratio to the ^{16}O Ground State for the ^{16}N Ground State (A. Heath and G. T. Garvey)

The branching ratio for ^{16}N ground-state decay to the ^{16}O ground state and 6.13-MeV level are 26 ± 2% and 68 ± 2%, respectively. Unfortunately, the errors in these determinations are highly correlated so that the ratio of these branches is $26{\pm}2/68{\mp}2 = .385 \pm .040$. This uncertainty is responsible for the bulk of the 11.5% error in our recent measurement of the beta decay rate of the ^{16}N $J^\pi = 0^-$, 120-keV level as it entered into the calibration of the beta detector efficiency. Reducing the error in the above ratio to 5% would reduce the error in the 0^- branch to 6.9%.

The measurement of the ^{16}N ground-state decay is being carried out at the Dynamitron using the $^{15}N(d,p)^{16}N$ reaction at $E_d = 1.7$ MeV. The beta rays are being measured in our flat-field beta spectrometer. The absolute acceptance of the spectrometer is being measured employing β-γ coincidences in the decay of ^{20}F made via $^{19}F(d,p)^{20}F$. We expect to be able to calibrate the absolute efficiency of this spectrometer to 3--4% thereby being able to measure the ^{16}N branching ratio to an acceptable level. This device will also be employed to measure the beta spectra associated with the fission of ^{255}Cf, an experiment which bears on the questions of γ spectra associated with heavy fissioning nuclei (U^{235}).

e. Neutron Beta Decay (S. J. Freedman, D. Dubbers,* J. Last,* P. Bopp,* H. Schütze,* and O. Schärpf†)

Data from the first measurements of the beta asymmetry using "PERKEO" (see Fig. I-8) in neutron decay have been analyzed. We find the asymmetry parameter to be $A = -0.1178 \pm 0.003$, somewhat larger but not inconsistent with previously obtained values. Figure I-9 shows the data for the energy dependence of the asymmetry. From the asymmetry we get $\lambda = |g_A/g_V| = 1.270 \pm 0.009$ after making appropriate corrections for weak magnetism and radiative effects. The inferred value for the neutron is 617.5 ± 7.2 seconds which is consistent with the shortest direct measurements. This result has important implications for weak interaction theory and cosmology. These preliminary results were presented at the Conference on Reactor-Based Fundamental Physics at Grenoble and a preliminary report will appear in the literature.

A new experimental run is planned to begin in April 1984. We expect to improve the asymmetry measurement, make a direct measurement of the neutron lifetime, and obtain the first measurement of neutron-weak magnetism effects.

---

*Physikalisches Institut, Heidelberg, Germany.
†Institut Laue-Langevin, Grenoble, France.

f. Study of the $^{10}B(2^-$, 5.11-MeV) and $^{10}B(2^+$, 5.16-MeV) Levels (S. J. Freedman and J. Napolitano)

As part of an ongoing feasibility study to measure iosvector parity mixing in the 5-MeV doublet in ^{10}B, we have measured the alpha-decay width of the 2^-,T=0 state at 5.11 MeV. Using the Physics Division Dynamitron, we explicity account for Doppler broadening and beam spread by measuring the thick-target yield shape for $\alpha + {}^6Li$ on the narrow ($\Gamma_\alpha \sim 1$ eV) 2^+, 5.16-MeV state. We find an RMS width of 300 eV for the beam width and Doppler broadening combined. Using the same technique we find $\Gamma_\alpha(2^-$, 5.11 MeV) and accurate calculations of the mixing matrix element, to estimate the magnitude of the effect observed in alpha capture on polarized ^6Li. This work has been accepted for publication. Future directions include confirming the value of $\Gamma_\alpha(2^+$, 5.16 MeV) and to establishing the relative $\ell=1$ and $\ell=3$ components for $\alpha + {}^6Li$ in the 2^-, 5.11-MeV state. We may also attempt to measure the parity mixing using the Argonne polarized ^6Li beam source at the University of Wisconsin Tandem Facility.

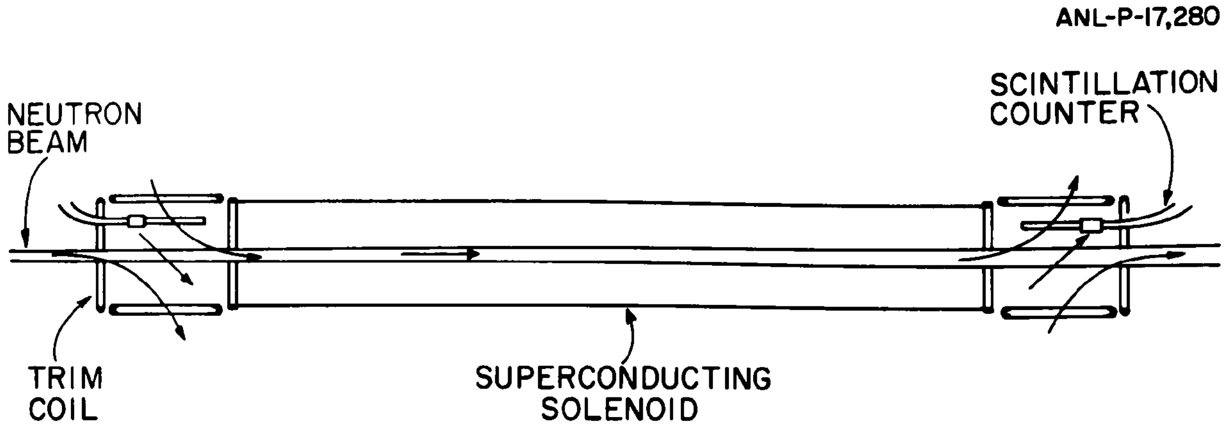

Figure I-8. Schematic layout of PERKEO.

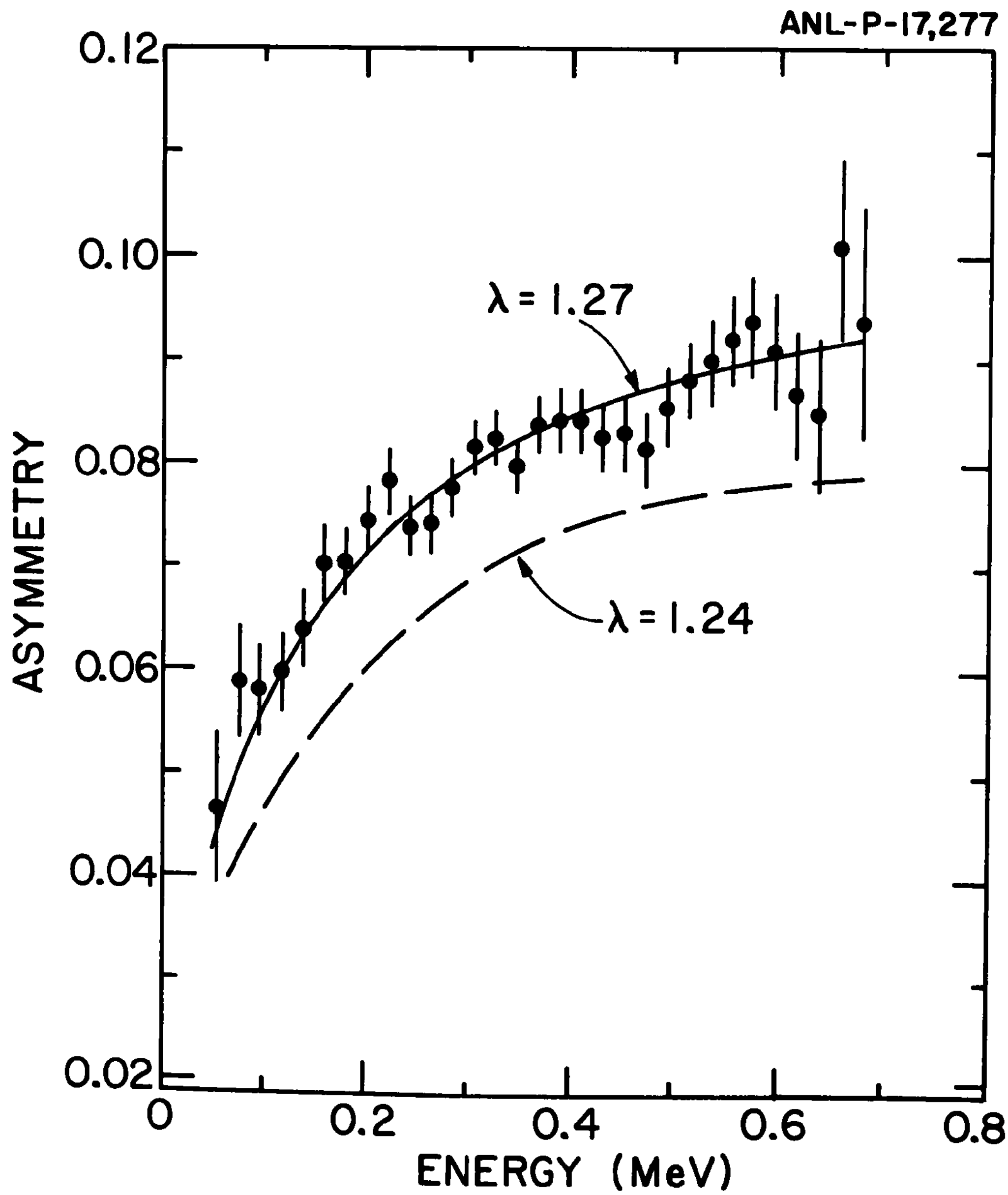

Figure I-9. Experimental β-ray asymmetry as a functi
curves are expectations for two values of λ.

g. The Ground-State Magnetic Moment of ^{7}Be (S. J. Freedman, L. Goodman and J. Napolitano)

We have begun an experiment to measure the ^{7}Be ground-state magnetic moment for the first time by nuclear magnetic resonance of ^{7}Be in solution. We plan to produce a ^{7}Be sample with the ANL Dynamitron. The ^{7}Be moment is important for magnetic-moment systematics and β-decay systematics of mirror nuclei. The ^{7}Be moment will be particularly valuable as a check on a recently-discovered and rather dramatic regularity in mirror nuclei.

h. Development of a Polarized ^{6}Li Accelerator Beam (S. J. Freedman, W. Habaerli*, P. Quin*)

The Argonne polarized ^{6}Li atomic beam source has been moved to the University of Wisconsin and modified to serve as a source for polarized ^{6}Li tandem beams. The necessary mechanical modifications have been made and the source has been extensively tested. For injection in the tandem ^{6}Li will be made into negative ions by electron exchange with a neutral Cs beam. Polarized beam intensities as high as 1 μA seem feasible. Experiments exploiting the new beam are being developed.

*University of Wisconsin.

i. $0^{+} \to 0^{-}$ Beta Decay of ^{16}C (C. A. Gagliardi, G. T. Garvey, N. Jarmie, R. G. H. Robertson)

Pseudo-scalar weak matrix elements have been studied as part of an endeavor to quantitatively determine the role of virtual pions in atomic nuclei. Well-rounded arguments establish that the best cases to observe such pionic effects occur in the time-like part of the weak axial-vector current such as enters into $0^{+} \to 0^{-}$ beta decay. The measurement reported here is the first observation of the decay of the ^{16}C ground state to the $J^{\pi} = 0^{-}$, 120 keV level in ^{16}N. The ^{16}C was produced via the $^{14}C(t,p)^{16}C$ reaction at $E_t = 6.00$ MeV at the LANL Tandem Van de Graaff. We find the log f_0t values for this decay to be $6.70^{+0.07}_{-0.05}$. The results of this experiment have been published.

j. Weak Magnetism Effects in Beta Spectra (J. Camp, G. T. Garvey, and D. Wark*)

A flat-field beta spectrometer with active collimation and a 3-wire detector with ray-tracing capability to permit background rejection has been built. It is intended to use this system to observe the effect of weak magnetism on the beta system shape. Previous experimental attempts to measure this effect have proven unsuccessful because of the small size of the effect, the order of 1% per MeV deviation from the allowed shape. The initial detection system constructed for the beta spectrometer did not perform well. Most of the problems encountered arose from the use of P-10 gas mixtures which left deposits on the wires and the drift fields for the electrons were too weak in extreme regions of the detector. These difficulties have been overcome with a new design which is presently evidencing adequate resolution and stability to be used in weak-magnetism experiments. We plan to measure weak magnetism in A=12 and 20 and possibly make a precision measurement of a $0^+ \rightarrow 0^+$ transition perhaps in A=42.

*California Institute of Technology, Pasadena, California.

k. Beta Spectra Following the Spontaneous Fission of ^{252}Cf (D. Wark,* G. Garvey, F. Boehm,* and J. Camp)

Neutrino-oscillation studies using reactor sources can be made much more sensitive if the ν spectrum from the reactor is known. The fission of a heavy nucleus such as Cf or U creates neutron-rich nuclei so far from the valley of stability that the their beta-decay spectra are not known. Thus a model must be employed to predict the overall beta-decay spectrum and the attendent ν spectrum. In order to test the reliability of the procedure used the beta spectrum of the fission fragments following ^{252}Cf fission is being measured. The activly-collimated, flat-field beta spectrometer is used. Its acceptance has been calibrated to much better than 5% and its momentum resolution is $\Delta p/p = 4 \times 10^{-3}$. One of the obstacles to performing the experiment is fabrication of a sufficiently intense ^{252}Cf source with high

*California Institute of Technology, Pasadena, California.

specific activity. Preliminary measurements with weak ^{252}Cf sources show that the neutrons produced during fission do not induce significant backgrounds at the detector. During the next year it should be possible to measure the beta spectrum out to 10^{-3} of its peak intensity.

E. PARTICLE SEARCHES

Modern field theories are formulated in terms of particles which have not been experimentally observed. The experimental identificaton of one of these particles would provide convincing evidence for the validity of the theoretical approaches. A reported observation of fractionally-charged objects in superconducting niobium lead to an accelerator-based search for fractionally-charged objects trapped in cryogenic materials. Grand unified field theories suggest that heavy magnetic monopoles exist. A search for slow-moving magnetic monopoles is currently underway.

a. A Cryogenic Experiment for the Detection of Fractionally-Charged Particles (W. Kutschera, J. P. Schiffer, D. Frekers, W. Henning, K. W. Shepard, C. Curtis* and Ch. Schmidt*)

The low-temperature-physics group at Stanford has persistently reported the observation of fractional charges on superconducting Nb balls. In these experiments a Nb ball of about 100-μg mass is levitated in a static magnetic field and the charge is determined from the response of the ball to an alternating electric field. Numerous searches in other laboratories using a variety of different (room-temperature) techniques have all yielded negative or inconclusive results. We have therefore performed an experiment with conditions similar to those of the Stanford experiment (superconducting Nb), however using a quite different detection technique.

One of the intriguing features of the Stanford experiment is the observation of frequent changes of the fractional charges when a Nb ball touched a solid surface between successive measurements. This suggests that the fractionally-charged particles present at liquid-helium temperature are loosely trapped in the superconducting Nb. These particles should readily be released when the temperature is raised and collection and acceleration in an electrostatic field should be possible. We have therefore built a Nb-filament source which could be cooled down to 4.2°K and rapidly heated up to several hundred °K. This source was installed on one of the Fermilab 700-kV Cockroft-Walton injectors and energy spectra of positively-charged particles extracted from the Nb filament were measured. Careful scans in the interesting energy regions of 1/3 and 2/3 the full energy were performed covering a mass range of about 10 MeV/c^2 to 100 GeV/c^2. No significant events were observed for a variety of different operating conditions. In particular, no increase in

*Fermi National Accelerator Laboratory, Batavia, Illinois.

counting rate was observed when the Nb filament was heated from liquid helium to room temperature.

The mass of the Nb filament in the present experiment was about 1000 times the mass of a Stanford Nb ball. If the fractional charges observed at Stanford are due to particles trapped in the ball, we should have seen 100-1000 events in the first few seconds after the heating. Since we observed no signals above the background of 10^{-2} per second we conclude that the fractional charges observed at Stanford are either carried by particles outside the mass range of our experiment or another hitherto unknown mechanism is responsible for their appearance.

b. A Search for Super-Heavy Particles in Cosmic Rays
(J. Dawson, S. J. Freedman, B. Gobbi,* M. Kroupa,† and J. Napolitano)

Magnetic monopoles with masses on the order of 10^{16} GeV/c^2 are predicted by Grand Unified field theories. Some astrophysical predictions of production rates of these objects in the early universe suggest an observable abundance in the present universe. Experimental searches for these objects have used two basic methods of detection. The first uses superconducting detectors to discover objects showing magnetic flux quantization. A single candidate for a magnetic monopole using this technique has been reported by Cabrera at Stanford. The second method attempts to observe magnetic monopoles by their ionization losses as they pass through matter. The major difficulty in this technique is the uncertainty in the amount of such losses for these slowly-moving particles.

Our search for these heavy magnetic monopoles consists of a layered array of large-area plastic scintillator counters with a geometrical factor of 3.8 m^2-ster. These counters, used previously in a search for low ionization by fractionally-charged particles, are sensitive to single photon or about 1.5% of the ionization of a single minimum ionizing particle. With data-acquisition electronics designed and prototyped by the High-Energy Physics Division, we are capable of sensing particles with velocities between 10^{-2} and 10^{-5} c. assuming any light is emitted by their passage.

*Northwestern University, Evanston, Illinois.
†Thesis Student, University of Chicago, Chicago, Illinois.

The data for each event includes the counters hit (latched), a 25 ns. scaler clock for each counter, and a pulse-height history of 300 μs around the trigger. A representative trigger event is shown in Fig. I-10. At present we have run 170 days without observing any candidate monopole events. This corresponds to an upper flux limit of 3 x $10^{-12}/cm^2$-s-str, a value comparable to similar experiments.

c. Search for a Light-Scalar Boson Emitted in Nuclear Decay (J. Camp,* S. J. Freedman, J. Napolitano, and M. Kroupa*)

There is very little experimental evidence to help us decide whether or not there exist light-scalar bosons with couplings like the Higgs boson. The existence of such a scalar would have profound implications for unified gauge theories or any fundamental theory of nature. Recently it was pointed out that a previous experiment putting limits on scalars in the range $6 < m_\phi < 18$ MeV/c^2 was improperly interpreted and actually too insensitive to be useful, thus the possibility of a light scalar was not excluded. We performed a new and very sensitive light-scalar search with the Physics Division Dynamitron using the apparatus shown in Fig. I-11. The resulting limits are shown in Fig. I-12. We looked for scalars emitted from the decay of ^{4}He(0^+, 20.2 MeV). The level was populated with resonance proton capture on tritium. We attempted to observe ^{4}He(0^+, 20.2 MeV) $\rightarrow$ ^{4}He(0^+, g.s) + ϕ using a heavily-shielded NaI detector. Only weakly-interacting particles like the Higgs would be able to penetrate the shielding and produce a signal in NaI by pair decay. Our experiment excludes Higgs-like scalars with $3 \lesssim m_\phi \lesssim 14$ MeV/c^2. A paper describing this work has been accepted for publication.

*Graduate student, University of Chicago, Chicago, IL.

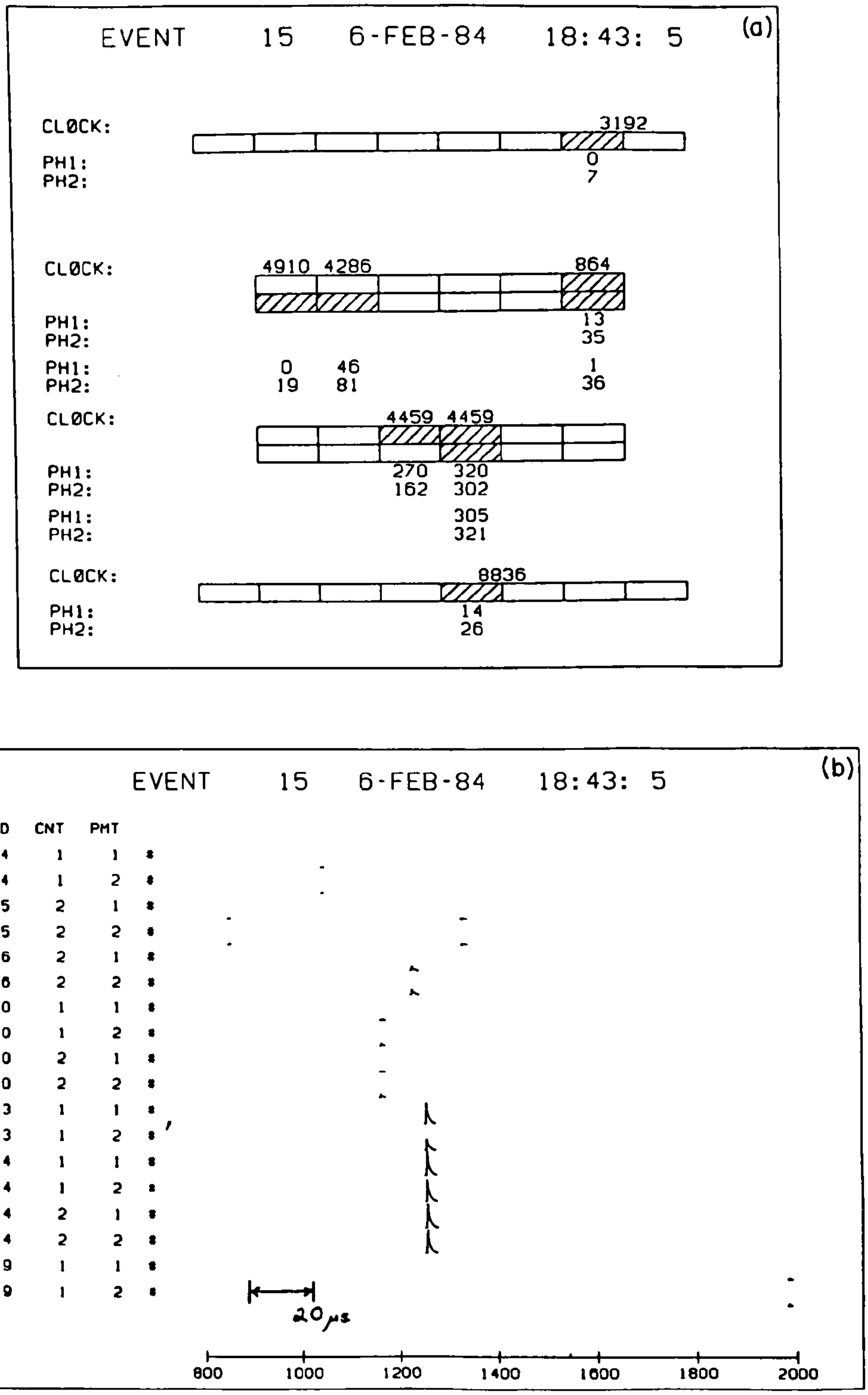

Figure I-10. A representative trigger event for the magnetic monopole search. (a)-the latched counters, 25 ns clock time and integrated pulse heights, (b)-the pulse-height history for the latched cou[redacted]

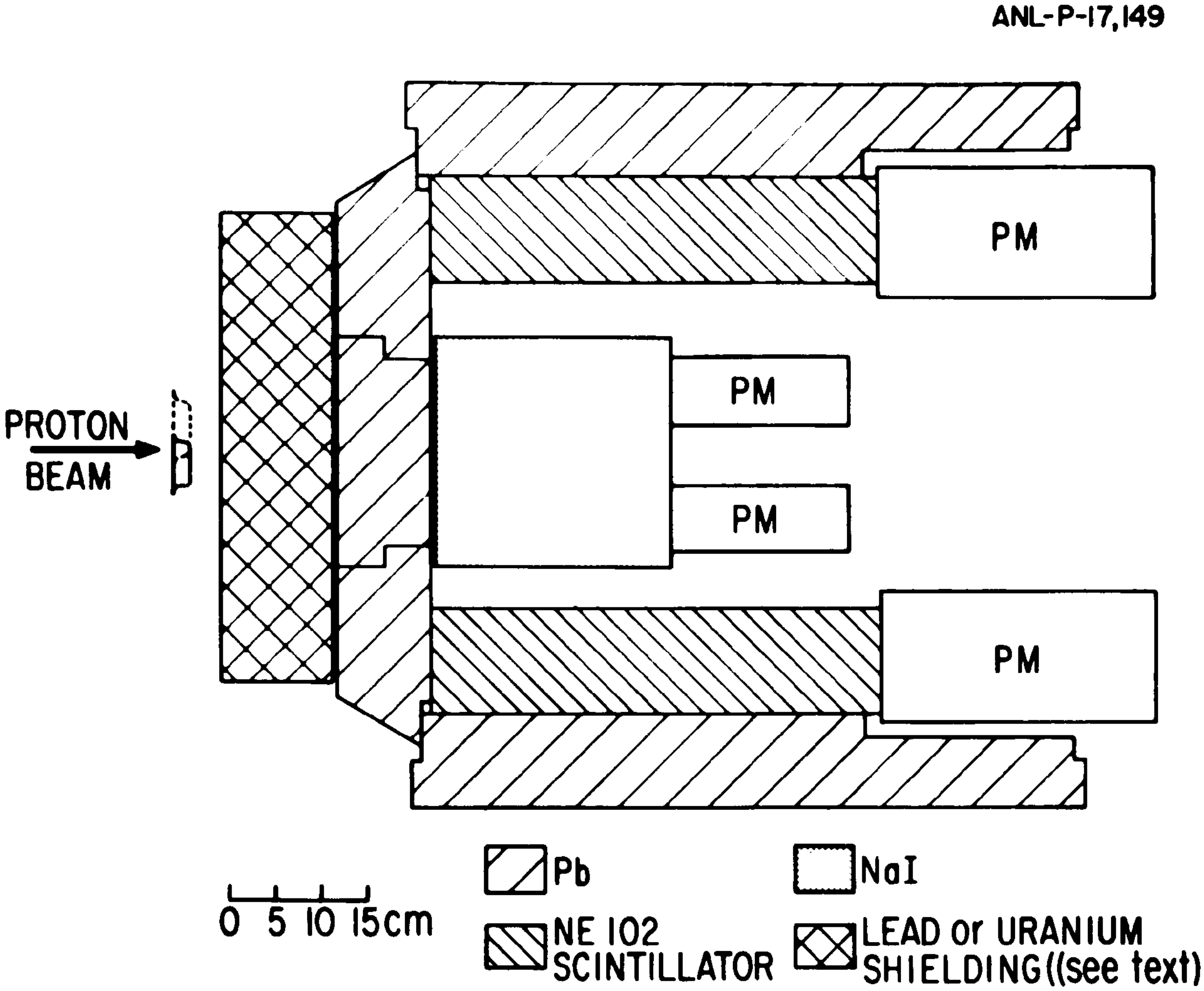

Figure I-11. Schematic diagram of the apparatus.

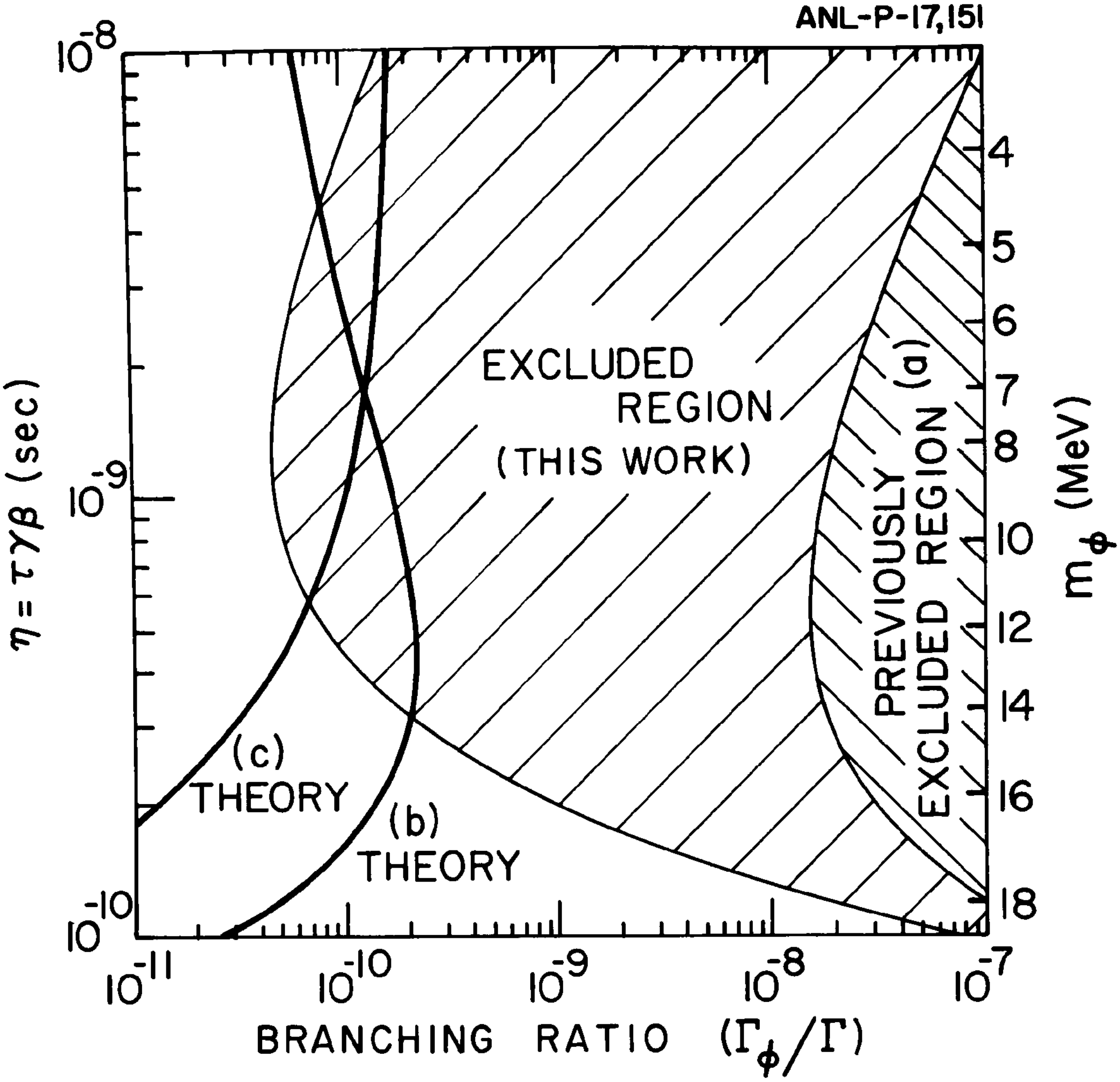

Figure I-12. The experimentally excluded region (at the 2σ level) in the lifetime-branching-ratio plane. The previously excluded region (a) (at the 2σ level) from Kohler et al. [Phys. Rev. Lett. 33, 1628 (1974] is calculated by our procedure with information from Kohler et al. The theoretical prediction (b) is from L. Resnick et al. [Phys. Rev. D 8, 172 (1973)] and (c) is from M. A. Shifman et al. [Phys. Lett. 78B, 443 (1978)] (if we assume four heavy quarks). The right-hand scale for m_ϕ refers to theories in which the ϕ coupling to d^+e^- is mass dependent in the standard fashion.

d. Measurement of the Electric Dipole Moment of the Neutron (V. E. Krohn, G. R. Ringo, T. W. Dombeck,* M. S. Freedman, J. M. Carpenter,† J. W. Lynn‡, and J. D. Moses*)

The purpose of this project is to measure the electric dipole moment (EDM) of the neutron. Such a measurement would probably constitute the most sensitive test of time-reversal symmetry now available. The present situation is that with about a factor-of-10 improvement in sensitivity, a whole class of gauge theories--those which explain CP failure by introducing a new scalar field [e.g., S. Weinberg, Phys. Rev. Lett. 37, 657 (1976)]--can be given a definitive test.

Since the measurement of the neutron EDM is fundamentally a frequency measurement, its statistical uncertainty is inversely proportional to the duration of the measurement. It is therefore natural to try the measurement on ultracold neutrons (UCN). These neutrons with $v < 7$ m/s can be kept in a bottle for hundreds of seconds. We propose to do this using two unique features. First, we propose to use a pulsed neutron source and keep the inlet to the bottle open only when the pulsed source is on, thus allowing a buildup to an asymptotic density determined by the peak flux of the source instead of the average. This has the advantage that pulsed sources have peak fluxes that are much higher than the average fluxes of steady-state sources of the same average power. Second, we propose to produce the UCN by Bragg reflection of considerably faster (400-m/s vs 7-m/s) neutrons from a moving mica crystal designed so that the reflected neutrons are almost stationary in the laboratory system. The advantage of this is that it avoids the problems of extracting the very delicate UCN from the hard-to-control environment in a high-flux source.

The present state of the project is that both of these ideas have been tested and shown to be practical as have several other ideas for enhancing the production of UCN, such as the use of reflectors around the moving crystal and funnels to concentrate the UCN in real space at the expense of their concentration in velocity space. The experiment has been seriously handicapped by the abandonment of the liquid-hydrogen moderators at IPNS and the delay in achieving 100°K moderation.

---

*Los Alamos National Laboratory, Los Alamos, New Mexico.
†Intense Pulsed Neutron Source, ANL.
‡University of Maryland, College Park, Maryland.

We have built a cold source of our own; polyethylene cooled by liquid nitrogen which works well in IPNS but while it is suitable for testing components of the experiment the neutron flux is too low for the actual EDM experiment which we plan to do at Los Alamos. There a possible source has opened up on beam line D, parasitic on the neutrino experiment on that line. It will quite probably be better for tests than IPNS and is a conceivable site for the full experiment although the WNR remains the most likely site for that.

At Argonne we plan to continue work on high-voltage tests of the measurement chamber, magnetic fields and magnetic shields, all this aimed at an experiment giving a limit of a few times 10^{-26} e•cm on the neutron EDM.

II. RESEARCH AT THE SUPERCONDUCTING LINAC ACCELERATOR

Introduction

The superconducting linac booster has been providing a very useful experimental facility in its present pre-ATLAS stage. The research program is constrained, not so much by technical limits, as by the increasing human resource that has to be devoted to planning the experimental system for the full ATLAS facility. A major area where the unique features of the present system are providing qualitatively new information is in measuring and characterizing quasielastic processes. In the region of the Coulomb barrier neutrons leaking from one nucleus to the other seem to account for a large fraction of the total reaction process, to an extent that was not expected before these measurements were carried out. Such quasielastic processes have a strong interplay with the magnitude of the fusion cross section, another process where the properties of the beams from the superconducting linac permit a wide range of experiments. Systematics of reactions for the lightest and heaviest Ni beams (^{58}Ni and ^{64}Ni) on all the stable even Sn isotopes (^{112}Sn to ^{124}Sn) are being determined experimentally, providing perhaps the most complete body of data for heavy-ion reaction studies. Work at the superconducting linac on the properties of nuclei at high angular momentum continues to lead to new insights into this domain of nuclear structure. The development of the experimental system for ATLAS includes a variety of projects. Among them is a large scattering facility, a BGO array for Compton suppressed gamma-ray spectroscopy as well as gamma-ray multiplicity and calorimetry measurements, and the further development of time-of-flight techniques, particularly in connection with a magnetic spectrometer.

A. QUASIELASTIC PROCESSES AND REACTION STRENGTHS

The availability of high-quality beams with masses $A \lesssim 80$ and with energies sufficient to overcome the Coulomb barrier for even the heaviest target nuclei, together with the availability of a high-resolution spectrometer in the form of the split-pole magnetic spectrograph with its sophisticated focal-plane gas detector, have allowed a research program concentrated on the quasielastic reaction processes in very heavy systems. These processes had generally been overlooked in reaction studies because they are difficult to resolve from the elastic-scattering contribution unless the experimental conditions mentioned above are available. This has also led to the belief that the contributions of these processes are small compared to the total reaction cross section. The present studies clearly reveal that this is not the case. The results show, among other things, that the neutron pickup reactions of Ni and Cl beams on targets of ^{208}Pb constitute ~25% of the total reaction cross section. They also show that neutron pickup of the projectile dominates even for such a neutron-rich beam as ^{64}Ni. The strengths of these and other quasielastic processes are expected to provide information on the transition from quasielastic to the deep-inelastic reaction channels. The large strength of the neutron-transfer channels has also allowed their direct observation in gamma-ray spectra, opening a new high-resolution method for these processes.

a. Large Cross Sections for Quasielastic Neutron Pickup Reactions Induced by ^{37}Cl, ^{48}Ti and ^{58}Ni on ^{208}Pb (K. E. Rehm, D. G. Kovar, W. Kutschera, G. S. F. Stephans, J. L. Yntema, and M. Paul *)

For reactions induced by medium-weight projectiles (A > 30) little is known about the contributions from quasielastic processes to the total reaction cross section, stemming to a large extent from the experimental difficulties to unambiguously identify the projectile-like fragments and resolving them from elastic scattering. We have started to investigate this question in reactions with beams of 250-MeV ^{37}Cl, 300-MeV ^{48}Ti and 375-MeV ^{58}Ni on ^{208}Pb targets. The outgoing particles from these reactions were momentum analyzed in the ANL split-pole spectrograph and detected in the focal plane with a position-sensitive ionization chamber. The measured parameters dE/dx, E_{total}, $B\rho$ (position) and the angle of incidence α (used to correct dE/dx) were used to obtain mass, nuclear charge and energy of the outgoing particles.

The reaction channels for these systems are dominated by neutron-pickup reactions e.g. (^{48}Ti, ^{49}Ti). (See Figure II-1). The energy spectra are generally bell shaped with a maximum at excitation energies between 6 and 12 MeV. Taking the ground-state Q-values into account we

*Hebrew University, Jerusalem, Israel.

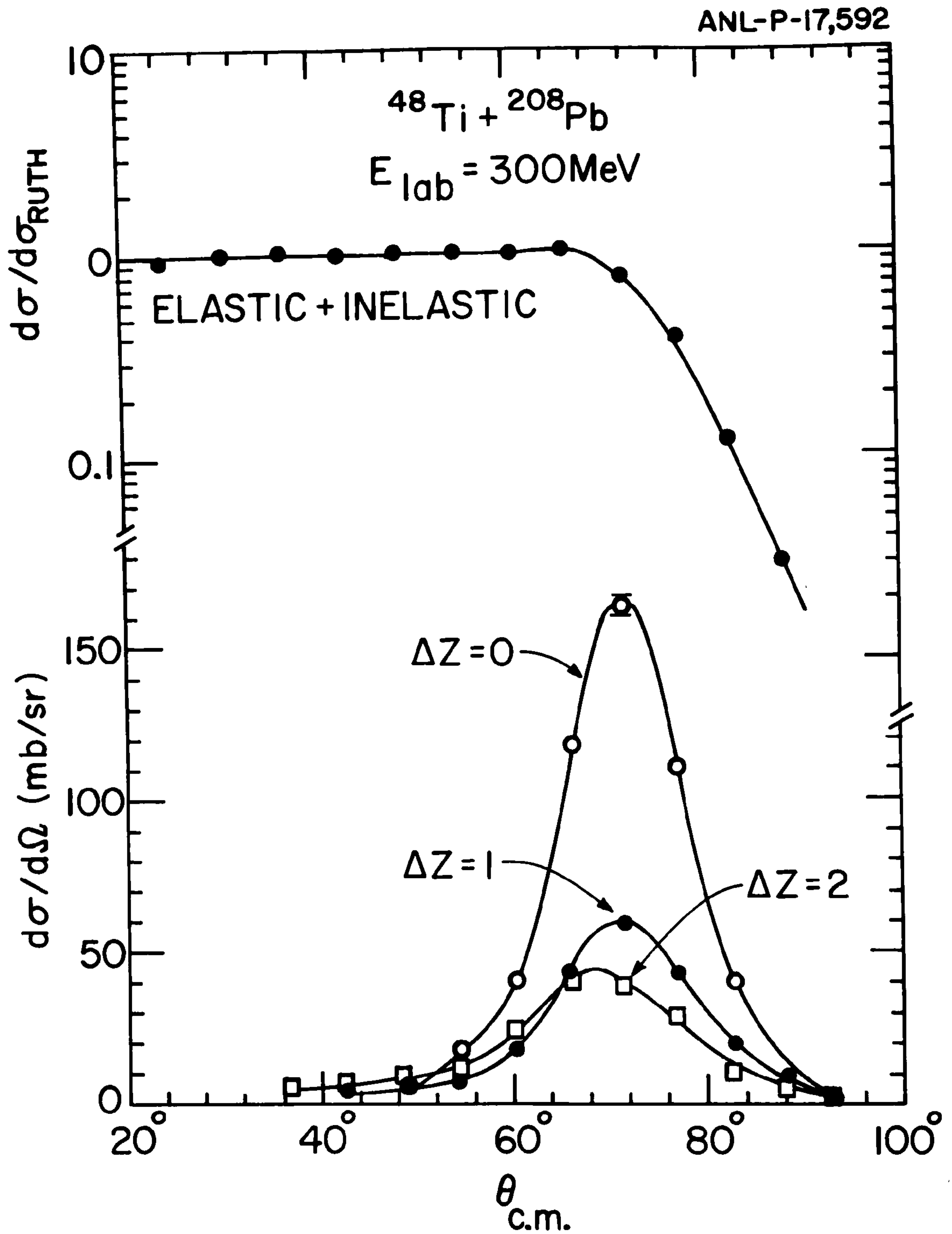

Figure II-1. Angular distributions for elastic scattering (including inelastic excitations up to 3 MeV), the neutron transfer reactions (ΔZ = 0) and the reactions (^{48}Ti,Sc) and (^{48}Ti,Ca) (ΔZ = 1,2 respectively) as observed for the system $^{48}Ti + {}^{208}Pb$ at E_{lab} = 300 MeV.

observe that the n-transfer channels are associated with effective Q-values (total kinetic energy losses) of ~ -5 MeV. The angular distributions from these reactions are bell shaped with a maximum slightly forward of the quarter-point angle. The integrated cross sections for all quasielastic n-transfer channels increase from 250 mb (^{37}Cl) to 380 mb (^{48}Ti) and 350 mb (^{58}Ni), which represents about 25% of the total reaction cross section for the latter two systems. The results from these measurements have been published.[1]

[1]K. E. Rehm et al., Phys. Rev. Lett. 51, 1426 (1983).

b. Energy Dependence of Quasielastic Neutron Transfer Reactions in the Systems ^{58}Ni + ^{208}Pb and ^{64}Ni + ^{208}Pb (K. E. Rehm, A. van den Berg, D. G. Kovar, W. Kutschera, L. L. Lee,* G. Rosner, G. S. F. Stephans, and J. L. Yntema)

Quasielastic neutron transfer reactions induced by medium-weight projectiles (A > 30) at energies close to the Coulomb barrier have been found to contribute up to 25% to the total reaction cross section. Reactions induced by ^{37}Cl, ^{48}Ti and ^{58}Ni are dominated by neutron pickup reactions like (^{58}Ni, ^{59}Ni) while neutron stripping reactions are much weaker. For the system ^{58}Ni + ^{208}Pb at E_{lab} = 375 MeV the ratio of the integrated cross section σ(pickup)/σ(stripping) is about 65:1. We have started to investigate the energy and projectile dependence of these processes in the systems ^{58,64}Ni + ^{208}Pb. ^{58}Ni and ^{64}Ni beams from the LINAC with energies between 345 and 380 MeV were used. The outgoing particles were detected in the focal plane detector of the split-pole spectrograph.

For the system ^{64}Ni + ^{208}Pb it was observed that a change in the incoming energy from 380 MeV to 355 MeV increases the contributions from quasielastic neutron transfer reactions to the total reacton cross section from 22% to 25%. This increase is more dramatic for the system ^{58}Ni + ^{208}Pb where an increase from 25% to 30% is observed, if the energy of the incoming particle is lowered from 375 MeV to 345 MeV. A similar strong neutron number dependence is observed if the relative importance of all quasielastic channels (processes with Q-values up to -30 MeV) and deep inelastic reactions (Q < -30 MeV) are plotted for the systems ^{58,64}Ni + ^{208}Pb (see Fig. II-2). While for both, quasielastic and deep inelastic reactions induced by ^{58}Ni, a strong energy dependence is observed, the two reaction processes are almost energy

*State University of New York, Stony Brook, NY.

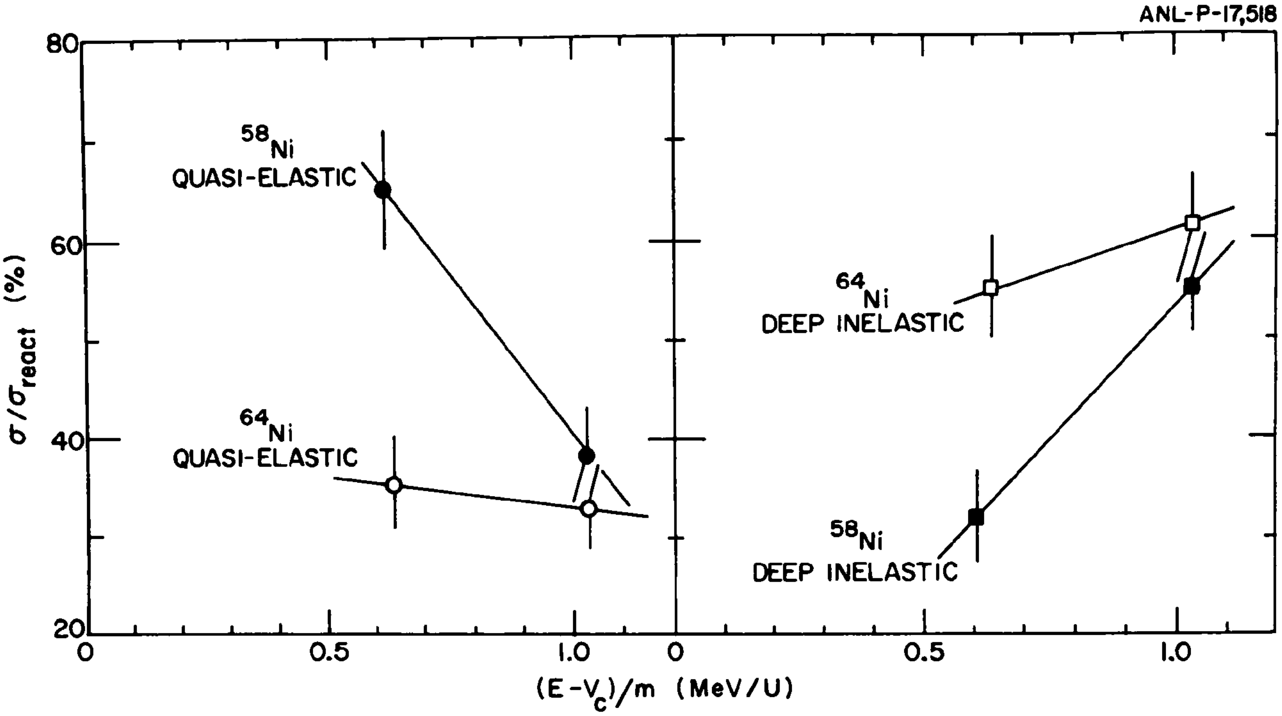

Figure II-2. Contributions of quasielastic ($Q > -30$ MeV) (left) and deep-inelastic ($Q < -30$ MeV) processes (right) to the total reaction cross section for the systems $^{58}Ni + ^{208}Pb$ and $^{64}Ni + ^{208}Pb$ as function of the energy per nucleon available above the Coulomb barrier.

independent for the system $^{64}Ni + ^{208}Pb$. We plan to extend these measurements to energies even closer to the Coulomb barrier.

c. Study of the Projectile Dependence of Transfer Reactions in the Systems $^{46,48,50}Ti + ^{208}Pb$ (K. E. Rehm, A. van den Berg, J. J. Kolata, D. G. Kovar, W. Kutschera, G. Rosner, G. S. F. Stephans, and J. L. Yntema)

In order to investigate a possible influence of the nuclear structure of the projectile on the magnitude of the transfer cross sections we have studied the systems $^{46,48,50}Ti + ^{208}Pb$ at $E_{lab} = 300$ MeV. ^{46}Ti has the highest B(E2) value for excitation of the first 2^+ state from all stable isotopes in the f-p-shell, while ^{50}Ti shows a closed $(f_{7/2})^8$ neutron structure. The beams were produced in the SNICS source from natural Ti-metal loaded with hydrogen. Particle identification was performed with the split-pole magnetic spectrograph and the position-sensitive ionization chamber in its focal plane.

The analysis of the data is presently in progress. For the neutron transfer channels we observe that the absolute magnitude of the cross sections is the same for the three systems $^{46,48,50}Ti + ^{208}Pb$ within the experimental uncertainty. The good mass and Z-resolution in our systems allows us to make Wilczynski plots for individual transfer channels. Some examples are shown in Fig. II-3 for the reactions (^{48}Ti, ^{49}Ti), (^{48}Ti,^{47}Sc) and (^{48}Ti,^{46}Ca) on ^{208}Pb. At large impact parameters (entrance phase) the reaction mechanism is dominated by the neutron pickup reactions which occur with very small energy losses [see the ridge at Q = 0 in the reaction (^{48}Ti,^{49}Ti)]. At the same time an "orbiting" component, correlated with energy losses up to ~100 MeV can be observed. These large negative Q-values must be correlated with very deformed configurations, the energy above the Coulomb barrier available in the entrance channel is only about 50 MeV. With increasing charge transfer [e.g. (^{48}Ti,^{47}Sc) and (^{48}Ti,^{46}Ca)] one observes a shift of the yield towards more negative Q-values and smaller contributions at small scattering angles with low energy loss. A detailed comparison with both DWBA calculations and macroscopic models is in progress.

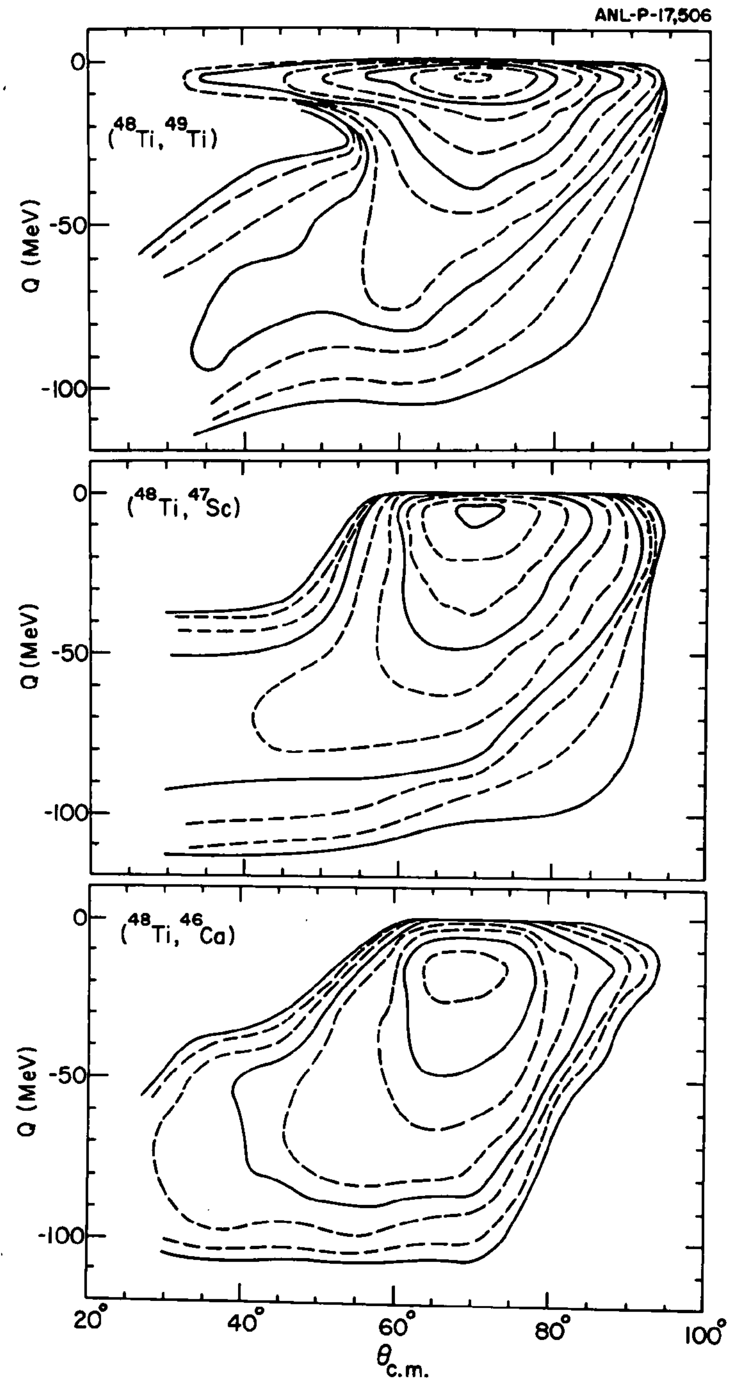

Figure II-3. Wilczynski plots (Q-value vs. $\theta_{c.m.}$) for three reaction channels for ^{48}Ti-induced reactions on ^{208}Pb at E_{lab} = 300 MeV. The outermost solid contour line corresponds to a cross section of 0.01 mb/rad, with an increaase by a factor of 10 for each subsequent solid line. Dashed lines are drawn at values of 0.2 and 0.5 times the values for the solid lines.

d. Quasielastic Processes in the $^{28}Si + ^{208}Pb$ and $^{28}Si + ^{40}Ca$ Reactions (J. J. Kolata,* R. Vojtech,† D. G. Kovar, G. Rosner, K. E. Rehm, G. S. F. Stephans, and K. T. Lesko)

Quasielastic processes (elastic and inelastic scattering and few-nucleon transfer) have been measured for the $^{28}Si + ^{40}Ca$ and $^{28}Si + ^{208}Pb$ reactions at $E_{lab}(^{28}Si) = 225$ MeV, using the split-pole magnetic spectrograph. An energy resolution of 400 keV was achieved in these experiments. The ^{208}Pb transfer data are characterized by large cross sections for one- and two-neutron pickup and single-proton stripping reactions. For example, the single-neutron pickup yield accounts for 12% of the total reaction cross section at this energy. Most of this strength is concentrated in a few states at excitation energies of 0-5 MeV above the ground state (Fig. II-4). The two-neutron pickup and single-proton stripping yields each exhaust about 4% of σ_{reac}, but the strength is at considerably higher excitation (5-15 MeV). All angular distributions exhibit the bell shape typical of peripheral collisions.

The strong excitation of the first 2^+ state in ^{28}Si suggests that channel coupling must be taken into account. We have been able to fit these data in the CCBA, and have shown the importance of including the hexadecapole deformation of ^{28}Si in the calculation (Fig. II-5). The ^{40}Ca transfer and inelastic data are still in the process of being analyzed.

*Permanent address: University of Notre Dame, Notre Dame, Indiana.
†University of Notre Dame, Notre Dame, Indiana.

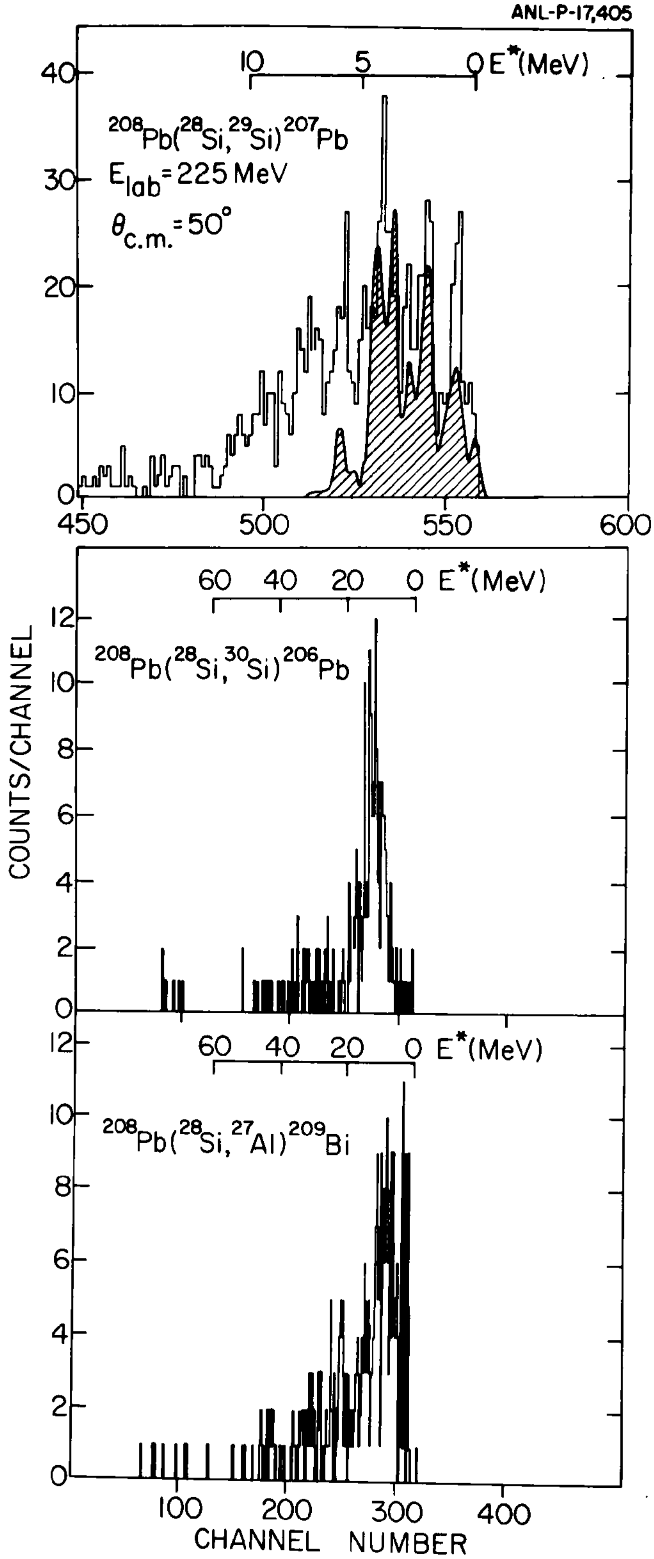

Figure II-4. Excitation energy distributions of ^{28}Si + ^{208}Pb transfer strengths at the grazing angle. The shaded curve is the result of a DWBA calculation including all states between 0-5 MeV of excitation having known spectroscopic factors.

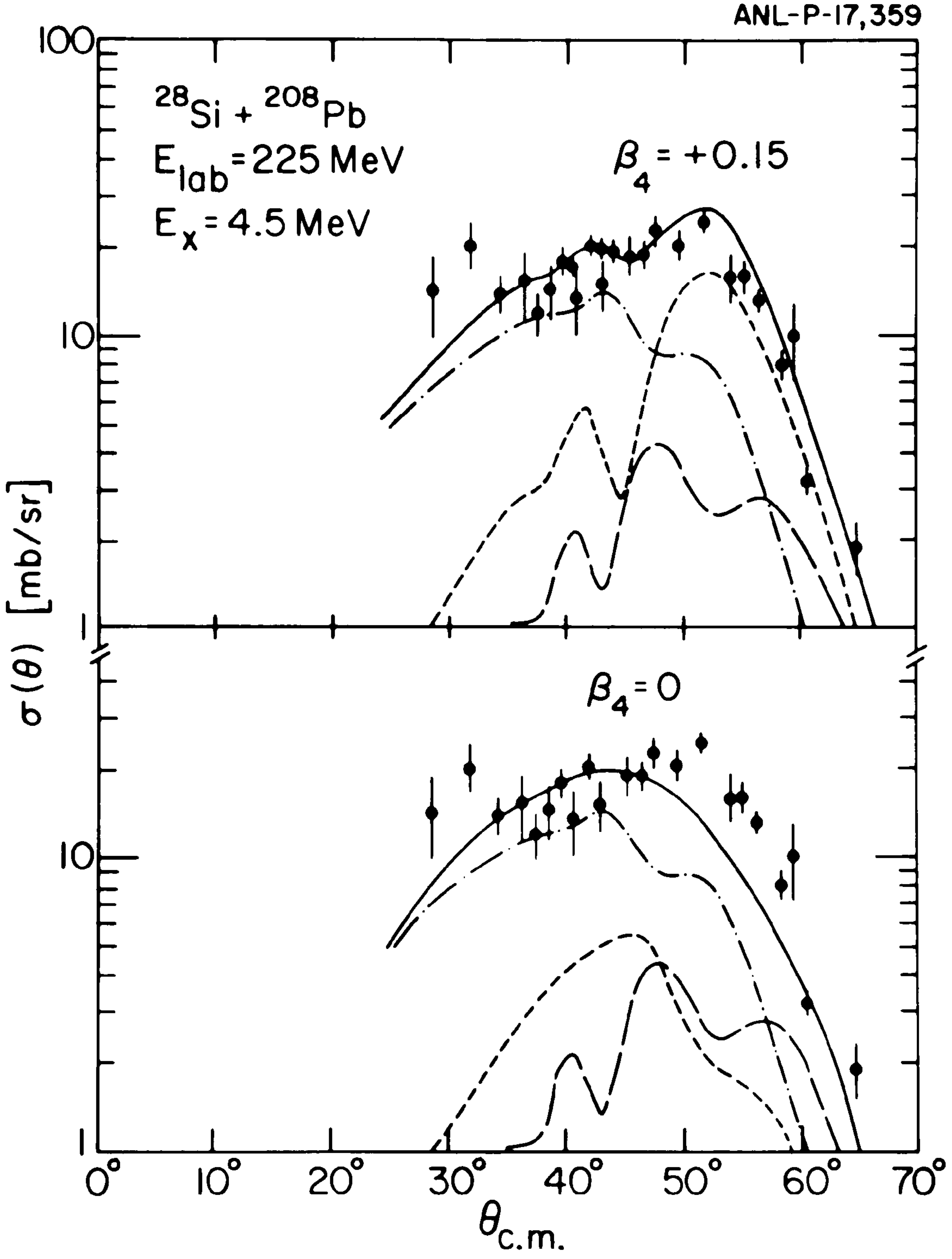

Figure II-5. Angular distribution for inelastic scattering to a multiplet at E_x = 4.5 MeV, which contains contributions from the first 4^+ state in ^{28}Si (short-dashed curve), the first 2^+ state in ^{208}Pb (dot-dashed curve), and the mutual excitation of the 3^- state in ^{208}Pb and the first 2^+ state in ^{28}Si (long-dashed curve). The solid curves show the predicted composite r the case β_4 = 0.15 (upper) and β_4 = 0 (lower), pole deformation parameter for ^{28}Si.

e. Heavy-Ion-Induced Neutron Transfer Reactions at the Coulomb Barrier Observed in Gamma-Ray Spectra (D. Frekers, R. V. F. Janssens, T. L. Khoo, and R. Broda*)

In a study of high-spin yrast states in the light Hg isotopes with $^{34,32}S$ beams on Gd targets, additional attention was given to exploring direct neutron transfer processes associated with the simultaneous Coulomb excitation (CE) of the target-like nucleus in the in- or out-going channels. It was found that the probability for transfer and excitation of high-spin states in the even (A $\pm$ 1) residual nucleus was comparable to the pure multiple Coulomb excitation of the (A $\pm$ 1) target.

For ^{156}Gd + ^{32}S (140 MeV) the dominant lines in the γ-ray spectra arise from multiple CE of the target, yet γ-lines from ^{154}Gd can clearly be identified indicating a significant 2n pick-up reaction cross section. With the ^{157}Gd target, the prominant γ-rays still originate from ^{156}Gd with an intensity comparable to the pure CE. For ^{32}S beams only pick-up reactions are observed, whereas with the ^{34}S beam the stripping process starts to compete. Multiplicity measurements indicate a considerably higher relative multiplicity for these transfer processes. This can be understood in a qualitative way: 1) A neutron transfer implies a close distance, at which simultaneous multiple CE of the residual nucleus is very likely. 2) Simple classical arguments favor slightly negative Q-values ($Q \simeq -1$ MeV) for the n-transfer reaction corresponding to excitation energies of about 3 MeV in the final nucleus. 3) The transfer of a predominantly $h_{9/2}$ neutron into a $d_{3/2}$ orbit favors reaction amplitudes that leave the residual nucleus in a high-j rotational state.

*Purdue University, W. Lafayette, Indiana.

f. Inelastic Scattering and Single-Nucleon Transfer Reactions Induced by ^{16}O on ^{40}Ca (G. S. F. Stephans, D. G. Kovar, W. Henning, J. J. Kolata, K. E. Rehm, G. Rosner, H. Ikezoe, R. Pardo, and R. Vojtech *)

Recent measurements of inelastic-scattering and single-nucleon transfer reactions for $^{16}O + ^{40}Ca$ at E_{lab} = 150 MeV have been performed. Reaction products were detected with an energy resolution of 150 keV using the split-pole magnetic spectrograph. Finite-range DWBA calculations were found to be successful in reproducing the strength of all single-nucleon pick-up and stripping reactions leaving one of the two nuclei in its ground state.[1] By contrast, similar calculations failed to reproduce the strength of ^{16}O-induced transfer reactions on ^{208}Pb at similar energies above the Coulomb barrier.[2] DWBA predictions of the shape of the $^{16}O + ^{40}Ca$ transfer angular distributions, which are forward peaked, were only fair (see Fig. II-6).

More sophisticated calculations including coupled-channel effects are being used to fit the 150-MeV $^{16}O + ^{40}Ca$ elastic data as well as previous data at energies down to the Coulomb barrier. Several energy-independent optical-model parameter sets have been found which reproduce this wide range of elastic data in DWBA calculations. An iterative procedure, varying only the imaginary parameters, was used to find complementary potentials which fit the data when coupled-channels effects are included explicitly. The influence of these different "bare" potentials on both inelastic and transfer-reaction calculations is being investigated.

*University of Notre Dame, Notre Dame, Indiana.

[1]G. S. F. Stephans et al., Bull. Am. Phys. Soc. 28. 717 (1983).

[2]Steven C. Pieper et al., Phys. Rev. C 18, 180 (1978).

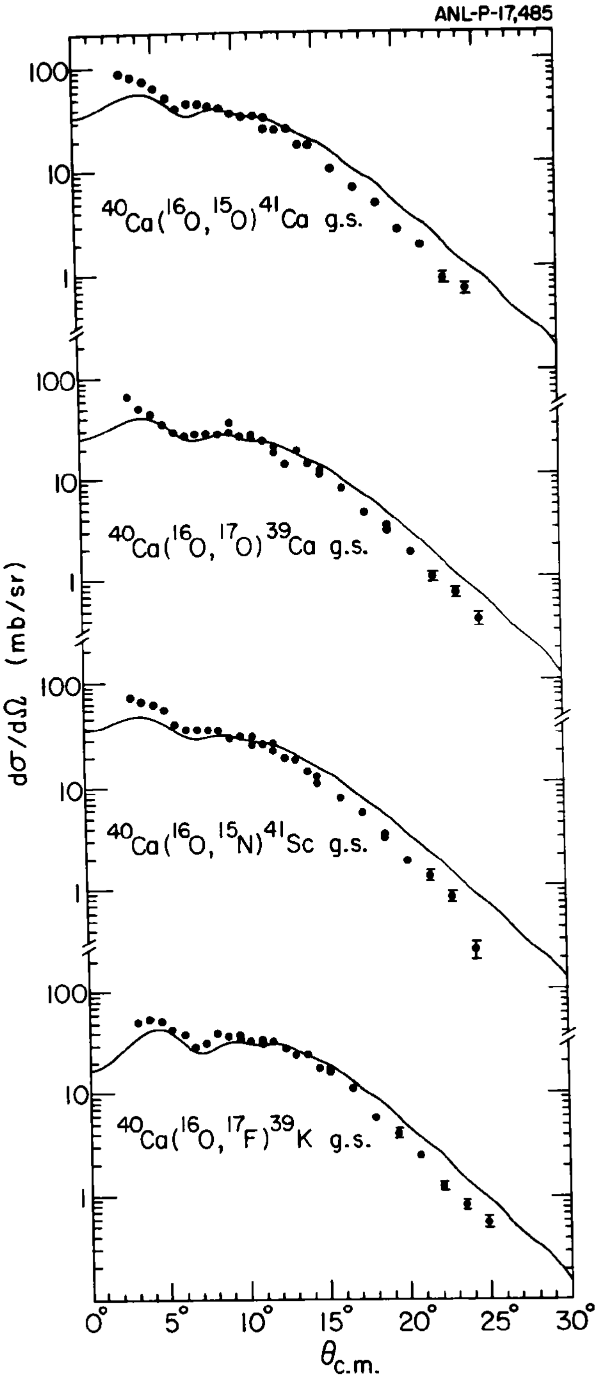

Figure II-6. Angular distributions of single proton and neutron transfer induced by ^{16}O on ^{40}Ca at 150 MeV leading to the ground states of the indicated nuclei.

B. FUSION OF HEAVY IONS

The fusion studies with heavier beams up to mass A = 70 represent a natural extension of previous work with lighter projectiles that was done with the tandem accelerator. Of particular interest is whether nuclear-structure effects are observed in the fusion of two such heavy nuclei, as well as the detailed nature of the fusion dynamics near and above the fusion barrier. A recently developed electrostatic-deflector system has been further improved to separate evaporation residues at and near 0° from the beam particles, and to allow concidences with prompt gamma and x-rays, and with light particles emitted from the compound nuclei and subsequent evaporation residues. To gain information on the properties and relaxation processes of nuclei formed in these fusion reactions, the decay through fission has been investigated for Ni + Sn over a wide range of neutron number and incident energy, covering the same range of systems for which detailed fusion measurements had been performed in the previous year. Extensive studies were performed to investigate processes of incomplete fusion where breakup and fragmentation of incident projectile or target lead to fusion of only parts of the involved collision partners. Velocity spectra of individually-resolved evaporation-residue-like masses have been used in both singles and coincidence measurements to obtain evidence of significant cross sections for incomplete fusion processes at higher bombarding energies for some projectile-target systems. Extrapolation of the fractional contribution of these processes to higher energies predicts that fusion of the full projectile-target system ceases to occur around 40 MeV/nucleon.

a. Fusion Cross Section Behavior For $^{10}B + ^{13}C$ and $^{11}B + ^{12}C$

(J. F. Mateja,* J. A. Garmon,* D. E. Fields,* A. D. Fawley,† D. G. Kovar, D. Henderson,‡ H. Ikezoe, R. V. F. Janssens, K. Lesko, G. Rosner, G. S. F. Stephens, and B. Wilkins †)

Time-of-flight measurements to establish the total fusion-cross-section behavior for the systems $^{10}B + ^{13}C$ and $^{11}B + ^{12}C$ have been performed in the energy range $4 < E_{lab} < 9$ MeV/nucleon to compliment results obtained at lower bombarding energies.[1] By studying two entrance channels which form the same compound nucleus (i.e. ^{23}Na) one hopes to understand whether the observed cross-section energy dependence is generated by limitations imposed by the compound nucleus or by entrance-channel effects. Previously reported results for light heavy-ion systems have shown that significant differences in fusion cross sections occur when the projectile or target is changed by one nucleon

*Tennessee Technical University, Cookeville, Tennessee.
†Florida State University,
‡Chemistry Division, ANL.
[1]J. F. Mateja et al., Phys. Rev. Lett. 47, 311 (1981); ibid, Phys. Rev. C 25, 2963 (1982).

or for different entrance channels forming the same compound nucleus.[2,3] However, not enough high-quality data have been obtained to draw firm conclusions regarding the reaction mechanism. The results of preliminary analysis appear to rule out over the energy range studied the possibility of a compound nucleus limitation.[4]

---

[2]J. Gomez del Campo et al., Phys. Rev. Lett. 43, 26 (1979).
[3]D. G. Kovar et al., Phys. Rev. C 20, 1305 (1979).
[4]S. M. Lee et al., Phys. Rev. Lett. 45, 165 (1980).

b. The Fission of Compound Nuclei Formed in Reactions of Ni + Sn
(K. T. Lesko, G. Rosner, W. Henning, K. E. Rehm, J. P. Schiffer, G. S. F. Stephans, B. Zeidman, and W. S. Freeman*)

A recent study of the fusion reactions for the systems ^{58,64}Ni + $^{112-124}$Sn has demonstrated a strong dependence of the maximum fusion-evaporation-residue cross sections on the compound-nucleus neutron excess.[1] To understand whether these dependencies indicate limitations to compound-nucleus formation or whether other exit channels can make up the differences, we have examined the fission channels for the same system at energies complementary to our earlier fusion measurements.

A coincident measurement was made observing both fission fragments. One fragment was observed by a gas ΔE, solid-state E time-of-flight spectrometer measuring the fragment's mass, charge, energy and position. The other fragment was observed in a large-area, position-sensitive gas-ionization detector. This counter measured the x- and y-position, charge and energy of the second fission fragment. Its large acceptance angle (~14 degrees out of plane, and ~35 degrees in plane) assured the detection of the coincident fragment for a wide range of Q values and mass asymmetries. Monitors placed in the forward hemisphere enabled us to obtain absolute cross sections by normalizing the observed yields to elastic scattering.

We measured the fission cross sections for both beams and the seven even Sn targets at 15 energies ranging from below the classical Coulomb barrier to well above it. This determines the dependence of the fission cross sections and also of the fission threshold on neutron number. Such systematic

---

*Fermi National Accelerator Laboratory, Batavia, Illinois.
[1]W. F. Freeman et al., Phys. Rev. Lett. 50, 1563 (1983).

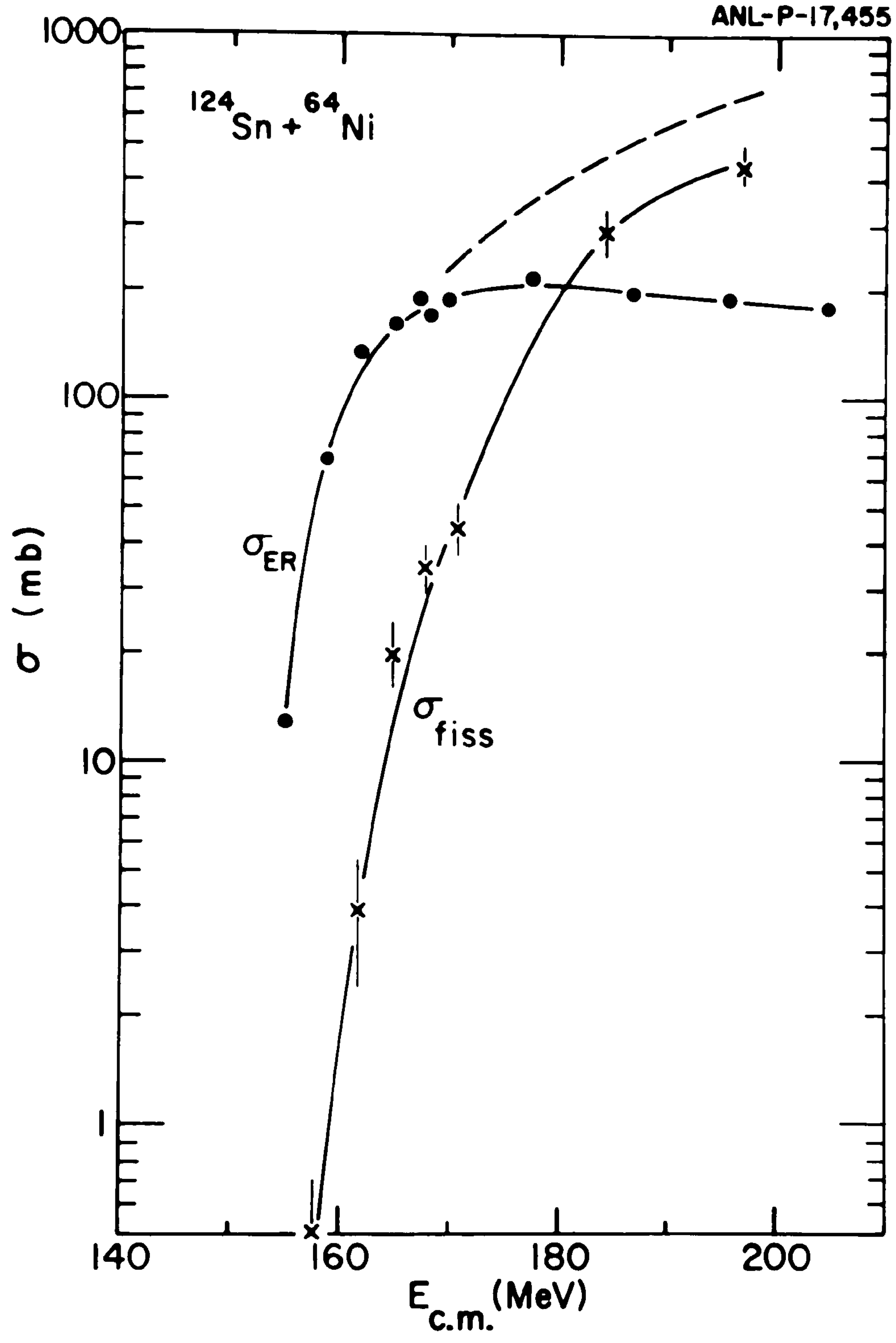

Figure II-7. Excitation functions of fusion-evaportion residue and fusion-fission cross sections for ^{64}Ni beams incident on a ^{124}Sn target.

dependences (≈20% change in neutron number for the same compound nucleus charge) had not been measured previously. Theoretical calculations, so-called dynamical collision models, have only recently begun to consider such effects. The analysis of these data, i.e. the extraction of the relevant cross sections, folding-angle distributions, and fission excitation functions is in progress. Preliminary results (for example Fig. II-7) indicate a stronger dependence of the fission barrier heights on neutron number than might be expected from simple models.

c. Projectile-Target Dependence of Incomplete Fusion Processes
(D. G. Kovar, G. Rosner, R. V. F. Janssens, D. Henderson,* H. Ikezoe, J. Kolata,† G. S. F. Stephans, K. Lesko, E. Ungricht, B. Wilkins,* F. Prosser, Jr.,‡ A. Szanto de Toledo,§ and E. Szanto §)

To obtain information regarding the projectile-target dependence of complete and incomplete fusion processes, measurements of the velocity spectra of the evaporation residues from fusion reactions have been performed using beams of ^{16}O, ^{24}Mg, ^{28}Si, ^{32}S on a series of light- and medium-weight target nuclei for comparison with the velocity spectra expected from complete fusion. Deviations from these expectations constitute evidence for contributions from incomplete fusion processes and provide an indication of their magnitude relative to the complete fusion contribution. The results for the reactions induced by ^{16}O and ^{28}Si have been completed,[1] and those for ^{24}Mg and ^{32}S are still in the process of being analyzed. The results for the asymmetric systems (i.e., $A_{proj.} < A_{targ.}$ and $A_{proj.} > A_{targ.}$) show evidence for significant contributions from incomplete fusion processes at the highest energies studied (E_{lab} = 7 MeV/nucleon) and are consistent with the interpretation that these processes are dominated by reactions involving particle emission from the lighter reaction partner prior to fusing. The symmetric systems ($A_{proj} = A_{targ}$) show little or no evidence for incomplete fusion contributions. Evidence that a strong entrance-channel effect exists is also apparent in the cross sections observed. For example, the $^{16}O + {}^{40}Ca$ reaction at E_{lab} = 160 MeV which has evaporation residue velocity spectra which deviate from that expected from complete fusion by 6%, has a total evaporation cross section of 1100 mb, while the $^{28}Si + {}^{28}Si$ reaction at a

*Chemistry Division, ANL.
†University of Notre Dame, South Bend, IN.
‡University of Kansas, Lawrence, KS.
§Universidade de Sao Paulo, Sao Paulo, Brazil.
[1]G. Rosner et al., Bull. Am. Phys. Soc. 28, 670 (1

ANL-P-17,081

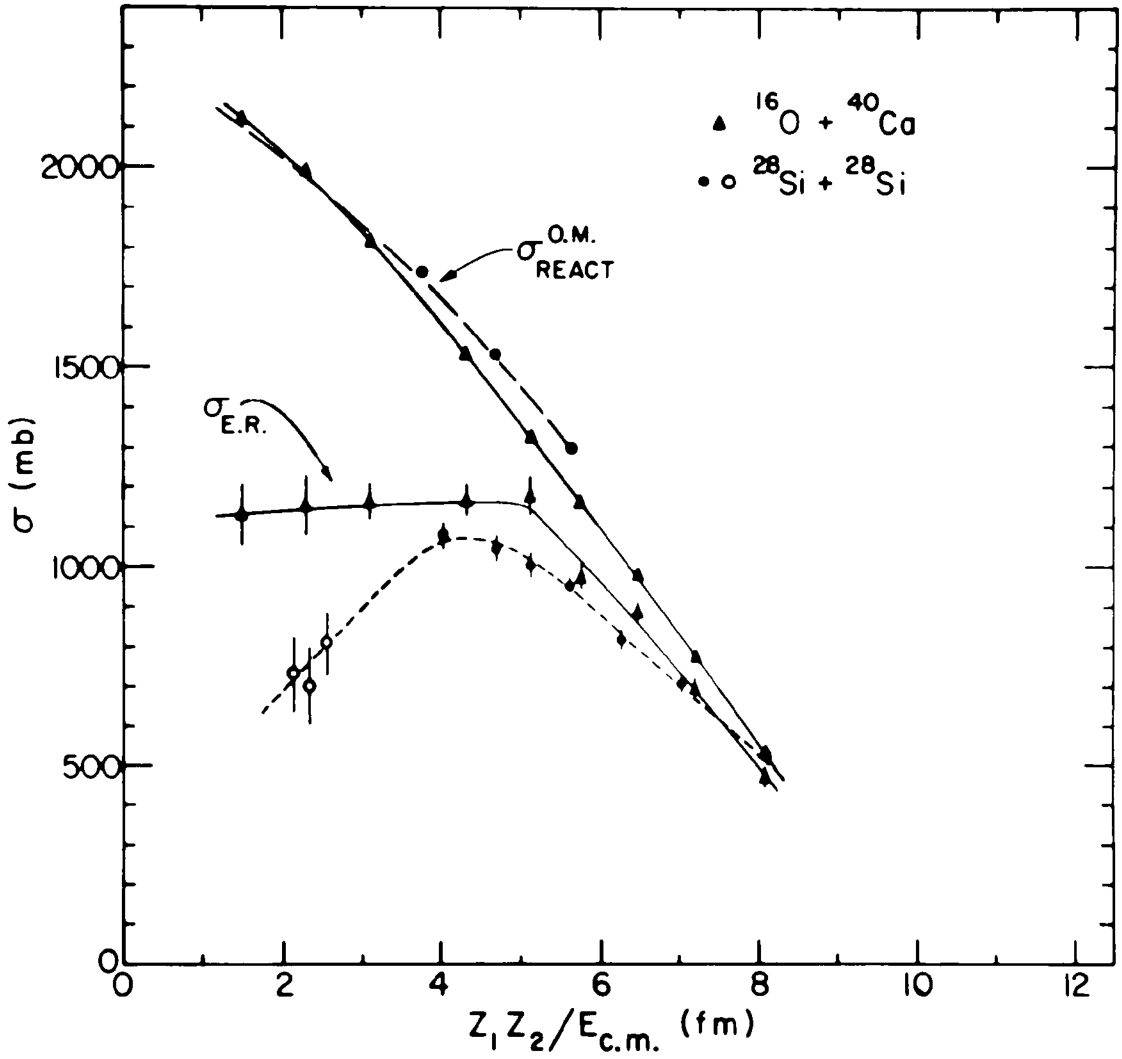

Figure II-8. Total evaporation residue cross sections for $^{16}O + ^{40}Ca$ (Ref. 2) and $^{28}Si + ^{28}Si$ (Ref. 1 and 3). The estimated total reaction cross sections are from optical-model calculations using DWBA for $^{16}O + ^{40}Ca$ and CCBA for $^{28}Si + ^{28}Si$.

comparable energy has velocity spectra consistent with complete fusion and a total evaporation residue cross section of 700 mb (see Fig. II-8). The results from the ^{24}Mg and ^{32}S measurements will provide additional information regarding the strong entrance-channel dependence observed. It is anticipated that coincidence measurements will be made for these systems to better understand the detailed reaction mechanism involved.

---

[2]S. E. Vigdor et al., Phys. Rev. C 20, 2147 (1979).
[3]S. E. Dicenzo et al., Phys. Rev. C 23, 2561 (1981).

d. Energy Dependence of Fusion Cross Sections for $^{24}Mg + ^{24}Mg$

(F. Prosser, Jr.,* S. V. Reinert,* D. G. Kovar, J. Kolata,† G. Rosner, G. S. F. Stephans, A. Szanto de Toledo,‡ E. Szanto‡)

Measurements of the evaporation residues from fusion reactions were made for the $^{24}Mg + ^{24}Mg$ system to establish the fusion-cross-section behavior over the energy range $5 < E_{lab} < 9$ MeV/nucleon. Previous measurements of the velocity spectra and cross-section behaviors for the systems $^{16}O + ^{40}Ca$ and $^{28}Si + ^{28}Si$ revealed a strong entrance-channel dependence. The velocity spectra observed in the $^{16}O + ^{40}Ca$ reaction showed evidence of contributions from incomplete fusion processes and a cross section which remained constant at about 1100 mb over an energy range $5 < E_{lab} < 10$ MeV/nucleon, while the velocity spectra from $^{28}Si + ^{28}Si$ showed no clear evidence of contributions from incomplete fusion processes and cross sections which decreased as function of bombarding energy. To investigate whether the behavior for the $^{28}Si + ^{28}Si$ system is typical of an identical nucleus system in this mass region or indicative of the properties of ^{28}Si, measurements for the $^{24}Mg + ^{24}Mg$ system were performed at three bombarding energies in the energy range comparable to that measured for the $^{28}Si + ^{28}Si$ system. The preliminary analysis indicates that the velocity spectra are consistent with the behavior expected for complete fusion and the cross sections are decreasing at higher bombarding energies in a manner similar to that observed in the $^{28}Si + ^{28}Si$ reactions. Future measurements of the other reaction channels for the identical nucleus systems will be pursued in order to investigate why the distribution of reaction strengths for these systems differ so much from that observed for non-identical systems.

---

*University of Kansas, Lawrence, KS.
†University of Notre Dame, South Bend, IN.
‡Universidade de Sao Paulo, Sao Paulo, Brazil.

e. Time-of-Flight Measurements of Evaporation Residues from the $^{32}S + ^{24}Mg$ System (J. J. Kolata,* J. Hinnefeld,† D. G. Kovar, R. V. F. Janssens, K. Lesko, G. Stephans, G. Rosner, B. Wilkins,‡ D. Henderson,‡ P. Gonthier,§ and F. W. Prosser, Jr.‖)

As part of a program to investigate incomplete fusion processes, the $^{16}O + ^{40}Ca$ and $^{28}Si + ^{28}Si$ reactions have previously been studied. The asymmetric $^{16}O + ^{40}Ca$ system shows considerably higher evaporation-residue yield than is observed for $^{28}Si + ^{28}Si$ at comparable energies above the Coulomb barrier (> 5 MeV/nucleon). Furthermore, the average evaporation residue velocities and widths for $^{16}O + ^{40}Ca$ show significant deviations from complete-fusion calculations at these higher energies, in the direction of incomplete momentum transfer, while the data for $^{28}Si + ^{28}Si$ are consistent with complete momentum transfer. As a further investigation of the mass-asymmetry dependence of this phenomenon, we have recently obtained time-of-flight spectra for individually resolved evaporation residues from the $^{32}S + ^{24}Mg$ reaction at $E_{lab}(^{32}S) = 290$, 250, and 200 MeV. The data are presently being analyzed at the University of Notre Dame. These data will be compared with the results of the $^{16}O + ^{40}Ca$ and $^{28}Si + ^{28}Si$ reactions which form the same ^{56}Ni compound system.

*Permanent address: University of Notre Dame, Notre Dame, Indiana.
†University of Notre Dame, Notre Dame, Indiana.
‡Chemistry Division, ANL.
§Hope College, Holland, Michigan.
‖University of Kansas, Lawrence, Kansas.

f. Evaporation-Residue-Velocity Measurements for Fusion of ^{14}N with Light Target Nuclei (G. S. F. Stephans, D. G. Kovar, R. V. F. Janssens, G. Rosner, K. T. Lesko, J. J. Kolata, P. Gonthier,* A. S. de Toledo,† E. Szanto†)

There is strong evidence from investigations of incomplete momentum transfer that these processes involve the emission of high-energy light fragments, especially α's, before fusion occurs. The ^{14}N measurements were performed to investigate the influence nuclear structure plays in the onset of incomplete momentum-transfer reactions and also to complement measurements recently performed with high energy ^{14}N beams at the Michigan State

*Hope College, Holland, Michigan.
†University de Sao Paulo, Brazil.

Cyclotron. Nuclear structure considerations suggest that the emission of α particles by ^{14}N might be inhibited relative to such nuclei as ^{16}O and ^{28}Si. As a result, there may be differences in the onset of incomplete momentum transfer for ^{14}N-induced fusion reactions.

Velocity centroids of evaporation residues were measured for ^{14}N-induced fusion on targets of ^{12}C, ^{24}Mg, ^{27}Al, ^{28}Si, and ^{40}Ca at beam energies of 129, 98, and 77 MeV. In addition, a fusion angular distribution was measured for $^{14}N + ^{40}Ca$ at 129 MeV in order to obtain the fusion cross-section. A TOF system including two channel plates and a Si ΔE-E telescope was used to produce precise velocity measurements and also allow detection of high-energy light particles.

Average evaporation residue velocities measured were less than the expected compound nucleus velocities by up to 7.5% at 129-MeV beam energy. Such a velocity deficit is consistent with a mechanism in which only part of the beam fuses with the target. The number of missing beam-velocity nucleons necessary to explain the measured velocity deficit was calculated for the results of this experiment and published data from other groups.[1,2] As shown in Fig. II-9, the "missing mass" depends linearly on the velocity of the lighter reaction participant in the center of mass. The lines are drawn to guide the eye. The slope of this dependence is significantly different for different beams.

This dependence can be understood qualitatively by considering the overlap of the Fermi spheres of the target and projectile with the Fermi sphere of the compound nucleus. For an asymmetric system, the center-of-mass velocity of the lighter fragment is larger than that for the heavier one. Similar ideas have been used by Bondorf and co-workers[3] in an attempt to explain light-particle spectra from heavy-ion reactions. The observation that

---

[1] Y. Chan et al., Phys. Rev. C 27, 447 (1983).
[2] H. Morgenstern et al., Z. Phys. A313, 39 (1983).
[3] E. Bondorf et al., Nucl. Phys. A333, 285 (1980).

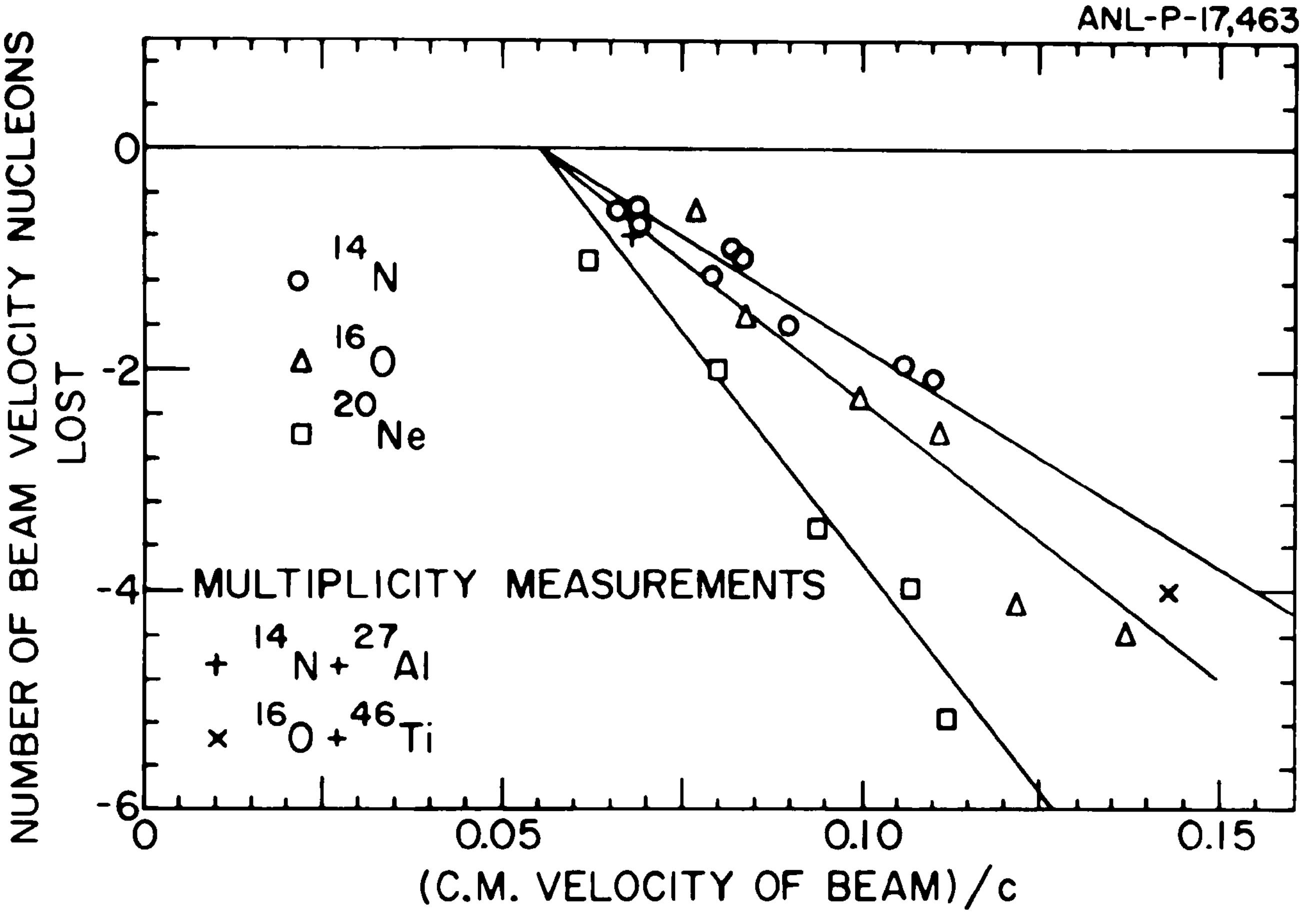

Figure II-9. Plot of the amount of mass that must be lost from the beam to explain measured evaporation-residue velocity deficits versus the velocity of the beam in the center of mass. In all cases plotted, the target is heavier than the beam. The ^{14}N data are from the present work and the Michigan State experiment described elsewhere in this report. Other evaporation-residue velocity data are from Ref. 1 for ^{16}O, and Ref. 2 for ^{20}Ne. The lost mass calculated from light-particle multiplicity measurements in coincidence with fusion-like residues are from Ref. 5 for ^{14}N and Ref. 6 for ^{16}O. Lines are drawn to guide the eye.

the ratio of incomplete-fusion cross sections to total fusion cross sections also depends linearly on the velocity of the lighter reaction partner has been made recently by Morgenstern et al.[4] Calculations have been performed assuming that the number of nucleons lost before fusion is simply the fraction of the projectile Fermi sphere outside the compound nucleus sphere times the mass of the beam. Fair quantitative agreement with the data shown in Fig. II-8 was found.

---

[4]H. Morgenstern et al., Phys. Rev. Lett. 52, 1104 (1984).
[5]R. Billerey et al., Phys. Rev. Lett. 47, 639 (1981).
[6]P. Gonthier et al., Nucl. Phys. A411, 289 (1983).

g. TOF Measurements of the Products of ^{14}N Induced Reactions at 15, 25, and 35 MeV/nucleon (G. S. F. Stephans, D. G. Kovar, R. V. F. Janssens, G. Rosner, B. Wilkins, H. Ikezoe, K. Gelbke,* B. Jacak,* Z. Koenig,* G. Westfall,* R. Fox,* C. Chitwood*)

Investigations of momentum transfer in heavy-ion fusion at high relative velocities (i.e. > 15 MeV/nucleon) have primarily involved the measurement of fission-fragment folding angular distributions. In order to extend the direct measurements of the recoil velocities of evaporation residues performed at Argonne to higher relative velocities, an experiment was performed at the Michigan State University Superconducting Cyclotron. A time-of-flight system including one channel plate and a ΔE-E Si detector telescope was used. Measurements of the velocities of individually-resolved evaporation residues were made at 5 degrees (lab) for targets of ^{12}C, ^{24}Mg, ^{27}Al, ^{48}Ti, and ^{58}Ni at ^{14}N energies of 15, 25, and 35 MeV/nucleon. Data were obtained simultaneously for projectile-like products of quasielastic and deep-inelastic reactions, as well as alpha particles up to and beyond beam velocity.

Evaporation residue velocities extracted from the velocity spectrum for individual masses were averaged over several masses to obtain the velocity of the fused system. The ratios of these velocities to the expected compound nucleus velocities (projected onto the angle the measurement was performed) are shown in Fig. II-10 along with the results of velocity measurements using other beams.[1,2] The velocity deficit increases roughly linearly with relative

---

*Michigan State University, E. Lansing, MI.
[1]Y. Chan et al., Phys. Rev. C 27, 447 (1983).
[2]H. Morgenstern et al., Z. Phys. A313, 39 (1983).

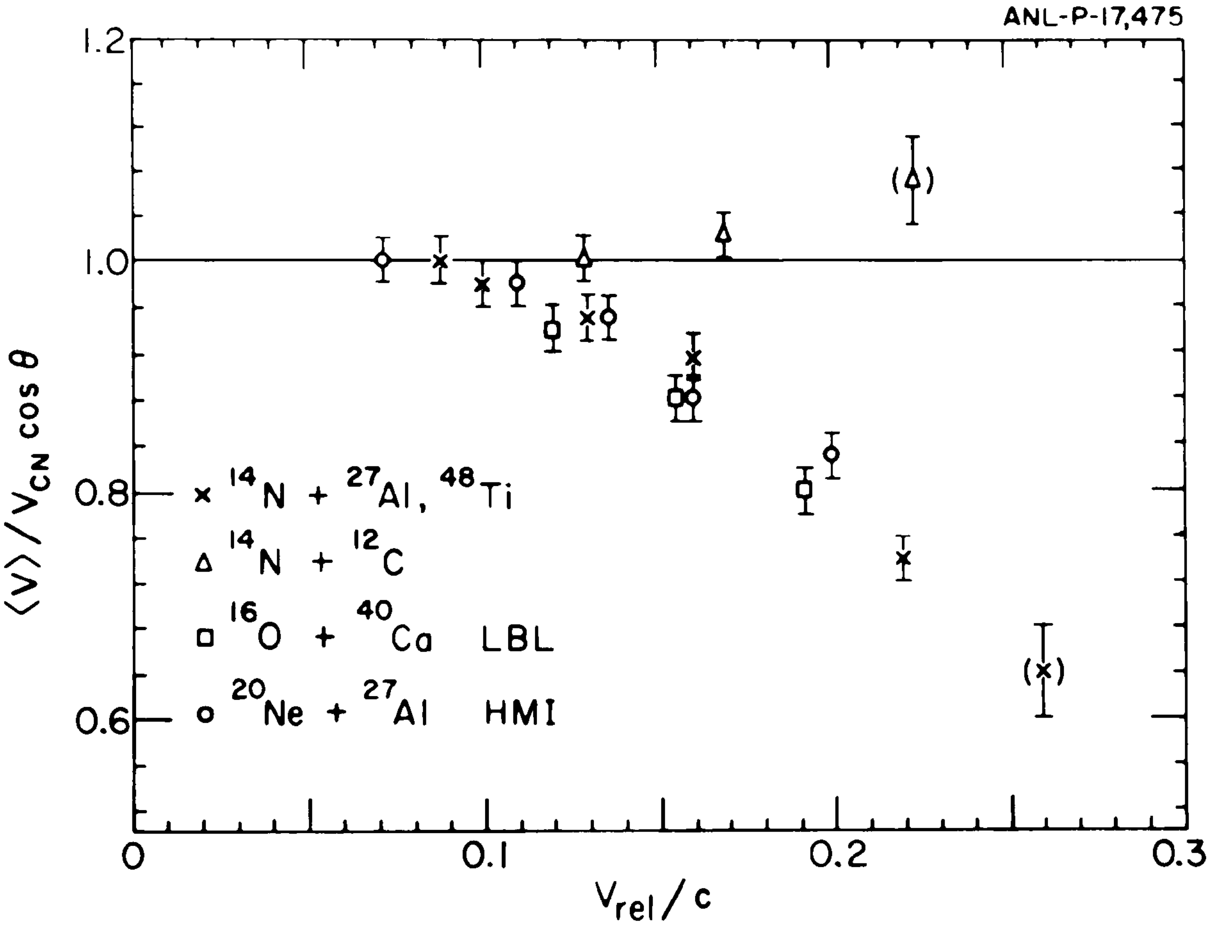

Figure II-10. The ratio of average evaporation-residue velocity to the expected compound-nucleus velocity plotted versus the relative velocity in the center of mass. The relative velocity has been corrected for Coulomb energy. The ^{16}O data are from Ref. 1. The ^{20}Ne data are from Ref. 2.

velocity in the center of mass up to the highest beam energies used. Detection of an evaporation-residue velocity less than the expected compound nucleus velocity suggests that only part of the beam fuses with the target. The measurements on the ^{12}C target are indicative of target breakup. Analysis of these data in terms of evaporation from an intermediate rapidity hot spot fails to reproduce the magnitude of the effect observed, indicating that a source of particles closer to the beam velocity must be present. The momentum widths of projectile-like fragments are currently being analyzed for comparison to various fragmentation models.

h. Coincidence Measurements Between Evaporation Residues and Light Particles Produced In $^{16}O + ^{40}Ca$ and $^{28}Si + ^{40}Ca$ Reactions

(H. Ikezoe, D. G. Kovar, G. Rosner, G. S. F. Stephans, E. Ungricht, B. Wilkins,* D. Henderson,* C. Maguire,† Z. Kui,† W. C. Ma,† S. Robinson,† D. Watson,† G. Work,† T. Awes,‡ and G. Young‡)

In order to investigate the reaction mechanism responsible for the production of the evaporation residues in the reactions $^{16}O + ^{40}Ca$ and $^{28}Si + ^{40}Ca$ at bombarding energies of E_{lab} = 9 MeV/nucleon, coincidence measurements between the evaporation residues and light particles ($M < 4$) were performed. Recent measurements have shown that at higher bombarding energies (i.e. $E_{lab} >$ 7 MeV/nucleon) a significant fraction of the evaporation residue arises from processes where a particle or particles are emitted from the projectile or target prior to fusion. Experimentally this is observed in the velocity spectra of the evaporation residues[1] and in coincidence measurements where the energy spectra of the light particles in coincidence with the evaporation residues have an energetic (beam velocity) component inconsistent with statistical emission from a compound nucleus.[2] In the present measurements we used both signatures of incomplete fusion processes in the attempt to better understand the details of the reaction mechanism and in the hope of more quantitatively distinguishing between the products of incomplete and complete

*Chemistry Division, ANL.
†Vanderbilt University, Nashville, TN.
‡Oak Ridge National Laboratory, Oak Ridge, TN.
[1]H. Morgenstern et al., Phys. Lett. 113B, 463 (1982).
[2]P. Gonthier et al., Phys. Rev. Lett. 44, 1387 (1980).

fusion. The evaporation residues were identified and their velocity spectra extracted using a 1-meter time-of-flight system. The light particles were detected and their energies measured in dE-E silicon surface-barrier-detector telescopes placed at six angles surrounding the heavy-ion detector. Preliminary results of the analysis of the $^{16}O + ^{40}Ca$ indicate that the incomplete fusion contributions, which account for about 30% of the evaporation residue yields, arise primarily from reactions where the ^{16}O projectile emits an alpha particle prior to fusing. The spectra of individual mass-evaporation residues in coincidence with protons and alpha particles, place severe kinematic constraints on any proposed reaction mechanism and hence have the potential for being useful tools for understanding the details of the reaction mechanism. The results of the $^{28}Si + ^{40}Ca$ system which are being analyzed at the present time will hopefully provide information regarding the projectile dependence of incomplete-fusion processes.

i. Systematics of Prompt Compound-Nuclear K X-rays in Fusion Reactions Induced by Heavy Projectiles (H. Ernst* and W. Henning)

The limits of complete fusion and compound-nucleus formation in a nuclear reaction induced by a heavy projectile are currently of great interest. As a possible sensitive indicator of low cross-section fusion reactions we have studied prompt K X-rays in compound-nuclear reactions induced by a heavy projectile, by determining total production cross sections and multiplicities of K X-rays from X-ray singles and X-ray--X-ray coincidences.[1]

Measurements for various targets (Ni, Zr, Sn) and projectiles (S, Cl, Ni) plus available data from the literature, indicate a strong dependence ($\approx A^7$) of the average X-ray multiplicity on compound nucleus mass A. This can be understood in terms of the increased conversion probability with nuclear charge ($\sim Z^3$) and decreasing average gamma-transition energy with increasing mass ($\sim A^{5/3}$). The results imply that compound nuclei beyond A $\approx$ 240 might emit in excess of five prompt X-rays for each fused nucleus, a potentially very powerful indicator for the formation of very short-lived superheavy nuclei.

*Technical University Munich, West Germany.

[1]H. Ernst et al., Phys. Rev. C 29, 464 (1984).

C. HIGH ANGULAR MOMENTUM STATES IN NUCLEI

Our studies have concentrated on shape changes which occur at high spin. Several studies were performed on transitional nuclei since those are soft with respect to the shape degree of freedom and thus most susceptible to shape changes. In several light Er, Dy and Ho nuclei the structure along the yrast line was found to change from prolate (i.e. well developed rotational band structure) to oblate with increasing spin. In ^{186}Hg, evidence for a change to a triaxial shape at moderate spin (~ 16) was found while prolate and oblate shapes coexist near the groundstate. The level structure of ^{147}Gd at very high spin was investigated further by means of lifetime measurements which confirm that up to the highest discrete states seen so far the oblate coupling scheme persists. A fast component in the feeding to these yrast states suggests, however, that collective excitations may exist above the yrast line. Considerable effort was devoted to the understanding of the origin of the suppression of neutron emission in fusion reactions with very heavy ions. Neutron spectra combined with the available information on the gamma decay suggest that in the initial stage of the reaction the nucleus may be trapped in a secondary minimum in the potential energy surface corresponding to a very large deformation ("superdeformation"). In the program studying the nuclei near the Z = 64 closed shell much effort was devoted to the systematic study of the very neutron-deficient N = 81 nuclei. Remarkable agreement with shell-model calculations was found.

a. Lifetimes of Very High Spin States in ^{147}Gd

(S. Bjornholm,* J. Borggreen,* J. Pedersen,* G. Sletten,* D. Frekers, R. V. F. Janssens, T. L. Khoo, and D. C. Radford)

Our first results on the spectroscopy of very high spin states in ^{147}Gd were recently submitted for publication.[1] The main results presented there can be summarized as follows: (a) states up to an excitation energy of 17 MeV and a spin of 79/2 were established, (b) the resulting decay scheme indicates single-particle nature up to the highest states with no evidence of collectivity near the yrast line. This interpretation is supported by shell-model calculations using a deformed potential. These calculations tell us also that within a few more units of angular momentum the nucleus now has to

*The Niels Bohr Institute, Copenhagen, Denmark.
[1]G. Sletten et al., Phys. Lett. 135B, 33 (1984).

find extraordinary ways of producing spin, either by exciting nucleons from the next major shell or by collective rotation.

In an attempt to distinguish between these two modes, lifetimes and feeding times of the upper states were measured by the recoil distance method with a plunger. This device was placed inside our sum spectrometer. Events of interest were selected by delayed tagging on the γ rays deexciting the 550-ns isomer in ^{147}Gd. The analysis is still in progress. Preliminary results indicate that at least 3 different lifetimes exist along the yrast line with values of 100 ± 20, 40 ± 5 and 25 ± 5 ps respectively. A fast component (< 3 ps) is present in the side-feeding to some of the yrast states. This may indicate that collective structures indeed exist above the yrast line in this nucleus.

b. Suppression of Neutron Emission in "Cold" Heavy-Ion Fusion: Comparison Between the ^{64}Ni + ^{92}Zr and ^{12}C + ^{144}Sm Reactions
(R. V. F. Janssens, T. L. Khoo, G. Rosner, W. Kühn,* R. M. Ronningen†)

In "cold" heavy-ion fusion reactions, where the excitation energy is low ($E^* < 50$ MeV), the relaxation of the initially highly deformed nucleus may be influenced by shell effects. For example, the system may be trapped in a secondary minimum in the potential energy surface corresponding to a larger deformation than normally observed near the ground state. We have recently published our results for the system ^{64}Ni + ^{92}Zr, forming the compound system ^{156}Er with $E^* = 46$ MeV.[1] Our measurements concentrated on the relative yields of the neutron-emission channels and on the neutron spectra corresponding to different γ-sum energies. When compared with results of statistical-model calculations, with parameters constrained to fit all available data, the experimental 2n/3n ratio is ~ 15 times larger than predicted. Thus there seems to be a suppression of neutron emission. One possible reason for this is that there is trapping in a potential well, as

*University J. Liebig, Giessen, West Germany.
†Michigan State University, East Lansing, Michigan.
[1] W. Kühn et al., Phys. Rev. Lett. 51, 1858 (1983).

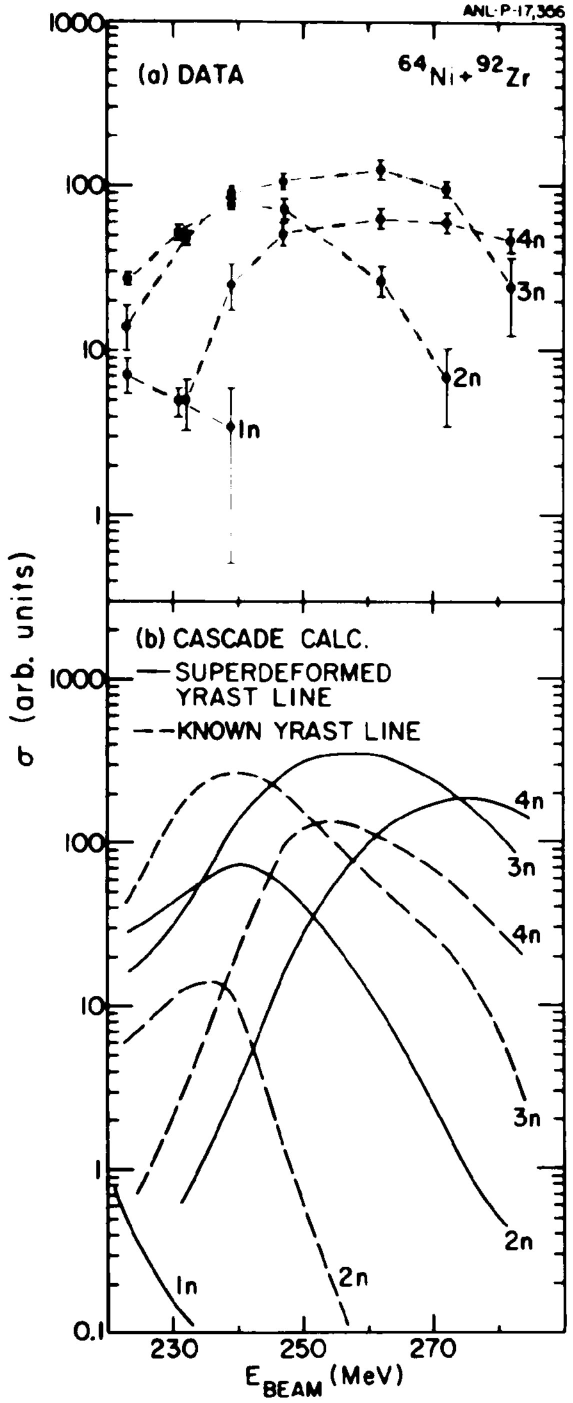

Figure II-11. Excitation function for the various neutron channels in the $^{64}Ni + ^{92}Zr$ reaction. Two calculations with the code CASCADE are presented. One (solid line) is performed with an elevated yrast line which corresponds to a nucleus with a superdeformed shape while the other (dashed line) assumes that the yrast line is the one known from γ-ray spectroscopy.

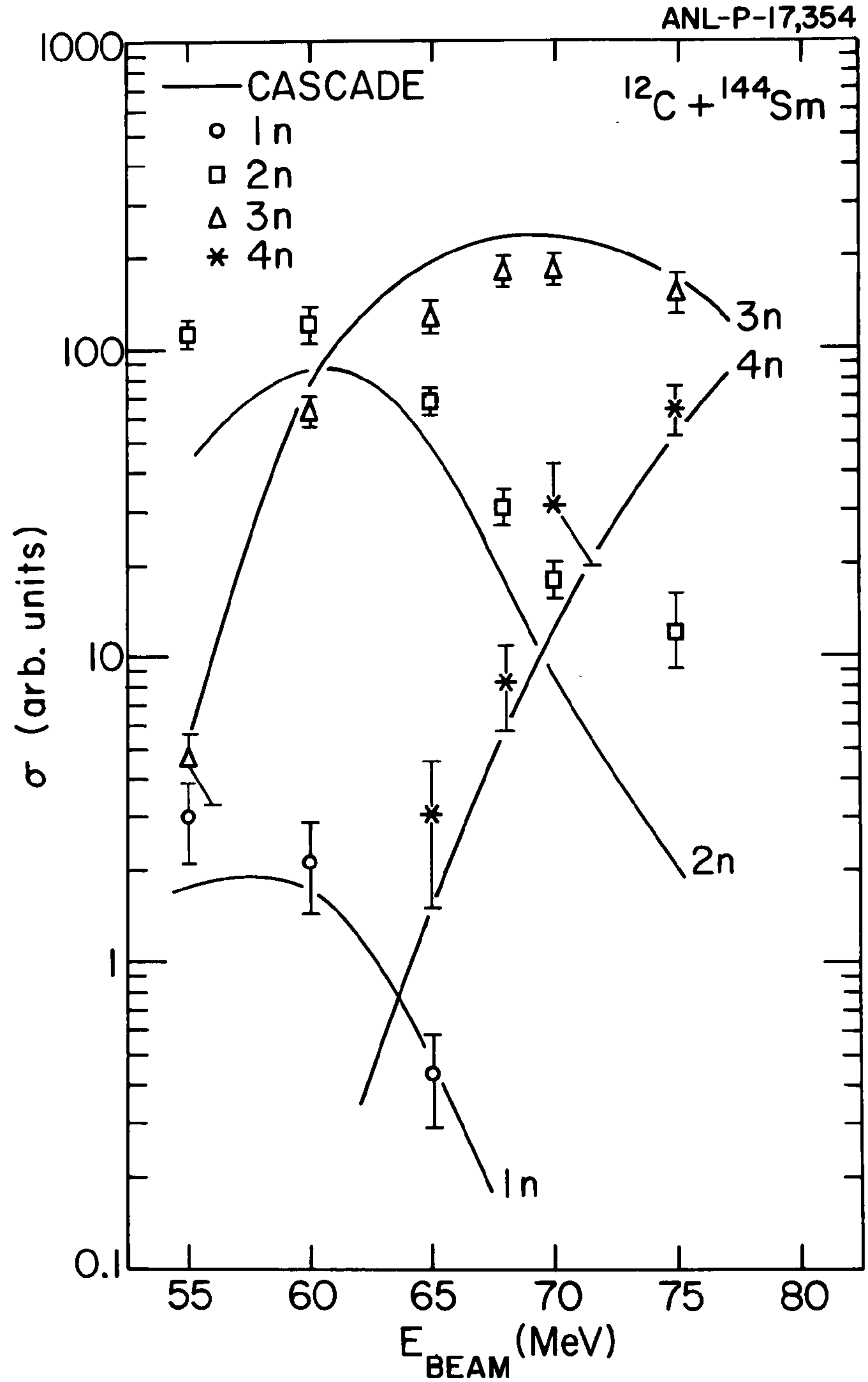

Figure II-12. Comparison between a CASCADE calculation and the data obtained for the reaction $^{12}C + ^{144}Sm$ at 6 energies.

described above, for a time longer than that for neutron emission. The available energy for neutron emission is then reduced, leading to the emission of fewer neutrons than might otherwise have been expected. In order to further test this hypothesis of trapping in a potential well, more experiments have been undertaken recently.

Relative yields of neutron-emission channels have now been measured for $^{64}Ni + ^{92}Zr$ at 8 beam energies (between 225 and 290 MeV) in order to test the energy dependence of the neutron suppression. The results can only be reproduced by statistical-model calculations (see Fig. II-11) when an yrast line elevated with respect to the known one is emphasized. This elevated yrast line follows the superdeformed minima in ^{156}Er calculated by Åberg.[2]

Another entrance channel to the same compound nucleus ^{156}Er was also investigated. Relative yields of the neutron emission channels have been obtained for $^{12}C + ^{144}Sm$ reactions at 6 beam energies (between 55 and 75 MeV). In this case, the mass asymmetry of the system is such that the occurrence of superdeformation is not expected. Hence, statistical-model calculations are expected to reproduce the data. This was verified experimentally: using statistical-model calculations with parameters constrained to fit all available data, good agreement with the observed neutron yields were found (see Fig. II-12).

---

[2]S. Åberg, private communication.

c. Entrance Channel Dependence in Compound Nucleus Decay Studied with the Darmstadt-Heidelberg Crystal Ball (T. L. Khoo,* R. V. F. Janssens, W. Kühn,† V. Metag,† D. Habs,‡ H. Gröger,‡ R. Repnow,‡ S. Hlavac,§ R. Simon,§ G. Duchin,‖ R. Freeman,‖ B. Haas,‖ and F. Haas‖)

In section C.b. we have noted that there appears to be a suppression of neutron emission in the fusion of ^{64}Ni and ^{92}Zr, whereas such a suppression is not present in forming the same compound nucleus ^{156}Er with the reaction $^{12}C + ^{144}Sm$. To study the origin of this effect we have performed experiments

---

*On leave at Max Planck Institute, Heidelberg, W. Germany.
†Physikalisches Institut, Universität, Giessen, W. Germany.
‡Max Planck Institute, Heidelberg, W. Germany.
§GSI, Darmstadt, W. Germany.
‖CRN, Strasbourg, France.

with the Darmstadt-Heidelberg crystal ball using the same two reactions. Two of the main purposes are to: (a) compare the decay modes in the two reactions for the same excitation energy and ℓ window, and (b) to completely characterize the decay of the compound nucleus.

The quantities measured include: the entry line, neutron and γ energy and multiplicity distributions, γ-angular distribution, and neutron angular anisotropy. In each case the measurements can be made for specific ℓ windows.

The analysis is still in progress but the following preliminary observations may be made. For the same excitation energy and ℓ windows, differences between the two reactions have been observed in the compound nucleus decay. The entry line in the Ni-induced reaction is ~3.5 MeV higher than in the C-induced reaction for γ multiplicities larger than 12. Correspondingly, there is a decrease in neutron emission in the Ni-induced reaction. Comparison of the γ spectra obtained from the two reactions reveal that the excess energy is released through electromagnetic decay in the Ni-induced reaction by photons of energy between 0.8 and 4 MeV. Finally, there are also differences in the feeding of the near-yrast states in ^{154}Er: in the C-induced reaction, a positive-parity band-like structure is significantly populated whereas in the Ni-induced reaction aligned high-J configurations are predominantly populated.

d. The Study of High Spin States in ^{155}Ho (D. C. Radford, T. L. Khoo, R. V. F. Janssens, R. Broda,* C. Carter,* P. J. Daly,* Z. Grabowski,* and J. McNeill*)

The nuclei ^{153,154}Dy have been extensively studied at this laboratory during the last 2-3 years.[1,2] In these nuclei a transition from collective rotational behavior to single-particle character is observed for the yrast levels, suggesting a change from prolate to oblate shapes. This transition occurs at different spins in the two isotopes (I > 32$\hbar$ in ^{154}Dy, I > 41/2$\hbar$ in ^{153}Dy).

*Purdue University, W. Lafayette, Indiana.
[1] A. Pakkanen et al., Phys. Rev. Lett. 48, 1530 (1982).
[2] M. Kortelahti et al., Phys. Lett. 131B, 305 (1983).

Such changes in the character of yrast levels are of particular interest, since they are a sensitive test of our understanding of the interplay between collective and single-particle modes of excitation. To further extend the systematics of the transition in this mass region we have chosen to study high-spin states in ^{155}Ho, an isotone of ^{154}Dy. To this end we have performed extensive γ-γ coincidence measurements, using the ^{122}Sn(^{37}Cl,4n) reaction and an experimental set-up consisting of 5 germanium detectors and a sum-energy NaI crystal. More recently we have measured the angular distribution of γ rays from this reaction. Analysis of both experiments is proceeding, and preliminary results seem to indicate a transition to oblate shape at a spin somewhat in excess of 55/2 ℏ.

e. Prolate, Oblate and Triaxial Collective Structures in the Light Hg Isotopes (R. V. F. Janssens, D. Frekers, T. L. Khoo, D. C. Radford, R. Broda,* H. Chung,* P. J. Daly,* Z. Grabowski,* and M. Kortelahti*)

The light Hg isotopes are located in a transitional region between spherical or slightly oblate nuclei and the well-deformed rare-earth nuclei. Evidence for shape coexistence has been reported for the light even-even Hg isotopes (i.e., A = 188-184). The present study aims at investigating the properties of the bands based on the coexisting prolate and oblate minima as well as at obtaining information on the evaluation of the nuclear shape as a function of spin and excitation energy. We have recently published the results of our γ-ray spectroscopic studies in ^{186}Hg, produced through the ^{156}Gd(^{34}S,4n) reaction.[1] In this nucleus, three bands with even spin and parity are observed; two of them are established up to high spin and are found to cross with little interaction at $I = 16^+$. Cranked shell-model calculations suggest that these two bands can be associated with a decoupled $\nu\ i_{13/2}$ pair based on a prolate and on an oblate or triaxial shape, respectively.

The studies of this nucleus have been continued. A 82 ± 5 μs isomer was observed and its decay has been established (see Fig. II-13). The latter proceeds mainly towards levels of the prolate band and through states of a band not observed in earlier investigations. A weak branch towards the 4^+

---

*Purdue University, W. Lafayette, Indiana.

[1]R. V. F. Janssens et al., Phys. Lett. 131B, 35 (1983).

ANL-P-17,307

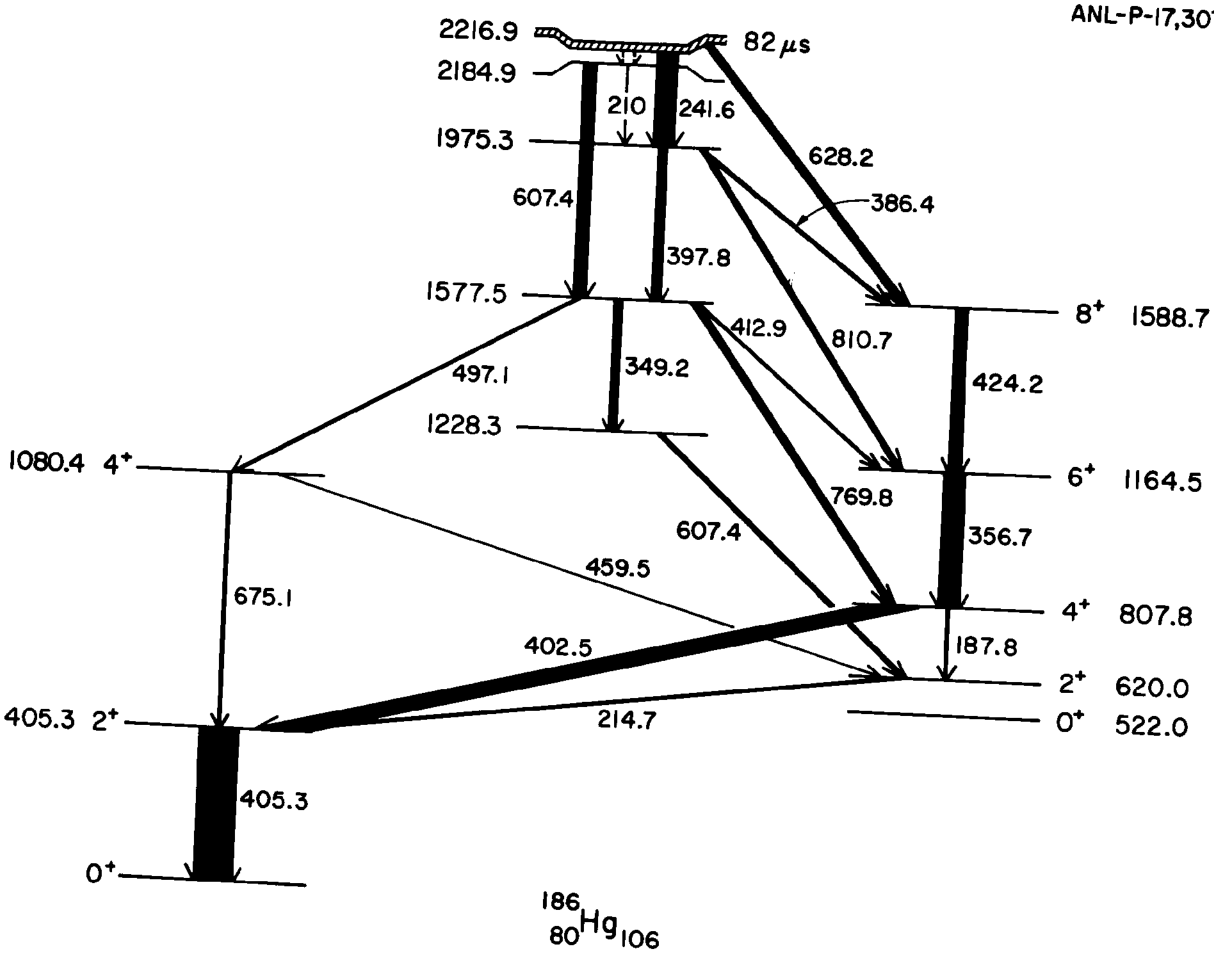

Figure II-13. Decay of an 82 μs isomer in ^{186}Hg.

state in the oblate band was also observed. The nature of this isomer is not well known and the precise knowledge of its spin and parity are necessary before an interpretation can be made. For this purpose, a measurement of conversion electrons is planned.

Further confirmation of the nature of the band structures observed in ^{186}Hg could be provided by an investigation of the odd-even neighboring isotopes ^{185,187}Hg. Information on ^{187}Hg was obtained from the ^{157}Gd(^{34}S, 4n) reaction through γ-γ coincidence, angular distribution and excitation function measurements. The analysis is in progress and is rather difficult. This is due to the complexity of the decay scheme which translates into the occurrence of a large number of weak γ-rays. Comparisons with band structures in ^{186}Hg and in heavier Hg isotopes will be performed and the cranked shell-model calculations applied so far to the even-even isotopes only will be tested further with the ^{187}Hg data.

f. <u>Nature of the Backbending in the Os-Ir-Pt Region</u> (R. Kaczarowski,* A. Chaudury,* E. G. Funk,* U. Garg,* J. W. Mihelich,* R. V. F. Janssens, D. Frekers, T. L. Khoo, D. C. Radford, and A. M. van den Berg)

The origin of the backbending phenomenon in the light Ir-Os nuclei has been a puzzling problem for some time. It was first suggested that the alignment of a $h_{9/2}$-proton pair is responsible for the backbending in the ground-state bands of the even Os isotopes. The discovery of a strong upbending in the decoupled band based on the $h_{9/2}$ 1/2$^-$[541] orbital in ^{183}Ir contradicted this hypothesis. It was subsequently suggested that the $i_{13/2}$ neutron orbital plays a decisive factor for the backbending behavior in this region. The differences in alignment and crossing frequencies for backbending in Ir and Os nuclei was then explained by the larger deformation of odd-even Ir nuclei due to the influence of the odd $h_{9/2}$ proton.

In order to check this explanation, lifetimes were measured in ^{181}Ir and ^{180}Os using the recoil-distance technique. The high-spin states in the two nuclei were populated by the ^{150}Nd(^{35}Cl, 4n) and ^{150}Nd(^{34}S, 4n)^{180}Os reactions, respectively. Use was made of the plunger device which fits into our sum spectrometer. The preliminary results of the measurements

---

*University of Notre Dame, South Bend, Indiana.

can be summarized as follows: In ^{180}Os two delayed components due to states at or above the backbending region are observed. One ($\tau \approx$ 10-20 ps) feeds the 8^+ state or higher. The other ($\tau >> 1$ ns) feeds states with $I >> 14$ in the yrast band. The precise location and the nature of these long-living states is unknown at present. The values of the intrinsic quadrupole moment Q_o for the 2^+ and 4^+ states in ^{180}Os and the $13/2^-$ state in ^{181}Ir as deduced from the respective lifetimes are equal within errors. This is inconsistent with the hypothesis given above that the different backbending behavior of Os and Ir is due to the larger deformation of the $h_{9/2}$ orbital. The higher levels of the $h_{9/2}$ orbital have Q_o values decreasing with increasing spin. This may suggest the onset of triaxiality with increasing rotational frequency or a reduction in prolate deformation.

In another experiment, the structure of ^{181}Ir was recently investigated towards higher spins through the measurement of γ-γ coincidences with the ^{150}Nd(^{35}Cl, 4n) reaction. The analysis is in progress. From the present measurements as well as from our data on the light Hg isotopes (see section I.C.d.) it is clear that changes in deformation play an important role in the behavior of these nuclei.

g. Shell-Model States in N = 81-83 Nuclei (R. Broda,* Y. H. Chung,* P. J. Daly,* Z. W. Grabowski,* M. Kortelahti,* J. McNeill,* R. V. F. Janssens, T. L. Khoo, R. D. Lawson, and D. C. Radford)

During the past year we have spent much effort on the systematic study of very neutron-deficient N = 81 nuclei just above the Z = 64 closed shell. Shell-model calculations, using ^{146}Gd as a closed core, have been extremely successful in describing the level structure of N = 82 and N = 83 nuclei previously. The N = 81 nuclei should yield excellent information on many additional matrix elements.

Using Ni beams from the tandem-linac accelerator and (Ni, pn) and (Ni, 2pn) reactions, we have obtained extensive delayed γ-γ coincidence data on ^{146}Tb, ^{147}Dy, ^{148}Ho, ^{149}Er and ^{150}Tm. In all the odd-odd nuclei, $J^\pi = 10^+$ isomers are observed with halflives of 1.18 ms (^{146}Tb), 2.35 ms (^{148}Ho) and 4.7 ms (^{150}Tm), all of which decay by E3 transitions to a 7^- state.

*Purdue University, W. Lafayette, Indiana.

These observations are in excellent agreement with shell-model considerations, which predict that the 10^+ member of the $(\pi h_{11/2}, \nu h_{11/2}^{-1})$ multiplet should be a yrast isomer, decaying to the $(\pi h_{11/2}, \nu d_{3/2}^{-1})7^-$ level. Similarly, $J^\pi = 27/2^-$ isomers are found in ^{147}Dy ($T_{1/2}$ = 460 ns) and in ^{149}Er. In the latter case, the spin assignment is not yet unambiguous, and the lifetime has been measured but not yet analyzed. These levels are expected to have a $(\pi h_{11/2}^{2}, \nu h_{11/2}^{-1})$ configuration. The β^+/EC decay of some of these N = 81 nuclei have also been investigated. Additional information has also been obtained for levels in ^{149}Ho, ^{150}Er (N = 82) and ^{152}Tm (N = 83). The analysis of the data collected this year will be finished by next year. Conversion electrons will also be measured in order to firmly establish the spins and parities of the states we have observed.

D. ACCELERATOR MASS SPECTROMETRY (AMS)

AMS experiments with the tandem alone ($T_{1/2}$ of ^{44}Ti, search for doubly-charged negative ions) have been completed and published. The Enge split-pole spectrograph used for these experiments has recently been moved to the new ATLAS target area III and future AMS experiments with heavier radioisotopes will utilize this facility. The main effort in the last year was concentrated on measuring the half-life of ^{60}Fe using the present tandem-linac system. A new half-life value was established demonstrating for the first time that such a combined accelerator system can be used in a truly quantitative way. An ambitious attempt with great initial success has been made to extend AMS to a very heavy radioisotope, ^{205}Pb. The measurement, performed in collaboration with a group from Munich at the heavy-ion facility UNILAC at GSI, may open the possibility of a geophysical solar-neutrino experiment with extremely low neutrino-energy threshold.

a. Half-Life of ^{60}Fe (W. Kutschera, P. J. Billquist, D. Frekers, W. Henning, X. Z. Ma,* L. F. Mausner,† R. Pardo, M. Paul,‡, K. E. Rehm, R. K. Smither, and J. L. Yntema)

The half-life of ^{60}Fe had been measured only once[1] yielding a value of $T_{1/2} = 3 \times 10^5$ y, uncertain by a factor 3. A more accurate value could be of considerable interest for a number of problems: 1) Extinct ^{60}Fe may be detectable in meteorites through ^{60}Ni isotopic anomalies,[2] thus providing information on the early history of the solar system, similar to ^{26}Al.[3] 2) The recent indication[4] of ^{26}Al in the interstellar medium suggests ^{60}Fe as another potential tracer of explosive nucleosynthesis. 3) The measurement of cosmic-ray-produced ^{60}Fe in meteorites (probably only feasible with AMS) may provide clues on cosmic-ray chronology in the million-year range. 4) The extent to which ^{60}Fe may have played an important role in the early heating of planetary bodies[5] depends critically on its actual half-life.

The half-life of ^{60}Fe was determined from the relation $dN/dt = -\lambda N$ using ^{60}Fe material ($\sim 10^{15}$ atoms) produced by spallation of Cu with 191-MeV protons in the Brookhaven Linac Isotope Producer (BLIP). One year after

---

*Institute of Atomic Energy, Beijing, People's Republic of China.
†Brookhaven National Laboratory, Upton, L. I., New York.
‡The Hebrew University of Jerusalem, Jerusalem, Israel.
[1]J.-C. Roy and T.P. Kohman, Can J. Phys. 35, 649 (1957).
[2]R. W. Hinton et al., Abstract submitted to Lunar Plan. Sci. Conf., Houston, (1984).
[3]T. Lee et al., Astrophys. J. 211, L 107 (1977).
[4]W. A. Mahoney et al., Astrophys. J. 262, 742 (1982).
[5]T. P. Kohman and M. S. Robinson, Abstracts 11th Lunar Plan. Sci. Conf., Houston, (1980) p. 564.

irradiation the iron fraction was separated carrier-free and quantitatively diluted with stable iron. Several aliquots of this material were prepared for $^{60}Fe/^{56}Fe$ ratio measurements with AMS and for measurements of the specific ^{60}Fe activity through the grow-in of the ^{60}Co daughter nucleus (1.33-MeV γ line). The AMS measurements were performed with the Argonne FN tandem-superconducting linac system using a split-pole spectrograph for heavy-ion detection. An ever-present strong ^{60}Ni background was separated from ^{60}Fe at an ion energy of 320 to 360 MeV with a passive-absorber technique[6] developed for measurements with high isobaric background. $^{60}Fe/^{56}Fe$ ratios in the range of 10^{-8} were measured under a variety of operating conditions in order to understand the overall uncertainties in using such a complex accelerator system for absolute isotope-ratio measurements (see Fig. II-14).

From the $^{60}Fe/^{56}Fe$ ratio and the γ-activity measurements (see Fig. II-14) we obtain a half-life of $(1.49 \pm 0.27) \times 10^6$ y (Ref. 7). This half-life is significantly longer than the previous value.[1]

---

[6] W. Henning et al., Nucl. Instrum. Methods 184, 247 (1981).

[7] W. Kutschera et al., Proc. 3rd. Int. Symp. on Accelerator Mass Sspectrometry, Zurich 1984, to be published in Nucl. Instrum. Methods.

b. Feasibility of Using the ^{205}Tl-^{205}Pb System as a Geophysical Detector for Solar Neutrinos (W. Henning, W. Kutschera, H. Ernst,* G. Korschinek,* P. W. Kubik,* H. Morinaga,* E. Nolte,* M. Müller,† D. Schüll†)

The detection of neutrinos is the only way to obtain direct information on nuclear processes in the interior of the sun. The only experimental result to date comes from the $^{37}Cl(\nu,e^-)^{37}Ar$ experiment of Davis et al.[1] who persistently measured a neutrino flux about three times lower than expected from the standard solar model. Despite the fundamental importance of understanding this discrepancy, no other neutrino-flux data are yet available for comparison. A variety of alternate targets has been proposed, every one of them having its particular problems. Besides radiochemical systems

---

*Technical University Munich, Garching, W. Germany.

†GSI Darmstadt, W. Germany.

[1] R. Davis, Jr. et al., Phys. Rev. Lett. 20, 1205 (1968); AIP Conf. Proc. No. 72, 295 (1980).

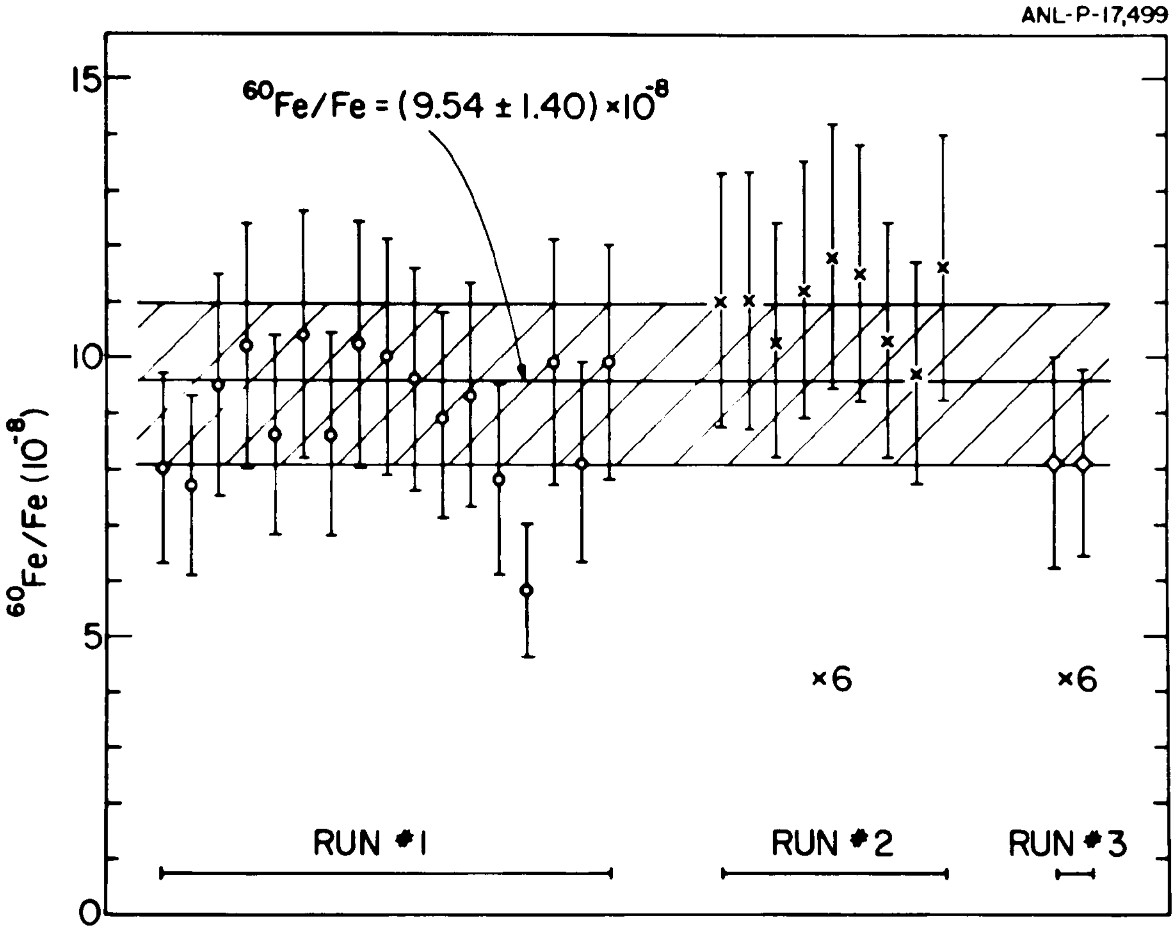

Figure II-14. Summary of the $^{60}Fe/Fe$ ratio measurements. Run #1 was performed in February 1983 with 360-MeV ^{60}Fe ions, run #2 in November 1983 and run #3 in March 1984 both at 320 MeV. The ratios measured in run #2 and #3 are multiplied by a factor of 6 to compare them with the previous measurement where material with a six-times higher ^{60}Fe concentration was used. Individual error bars include both systematic and statistical uncertainties. The value for the $^{60}Fe/Fe$ ratio shown in the figure represents the unweighted mean and standard deviation of the 28 data points.

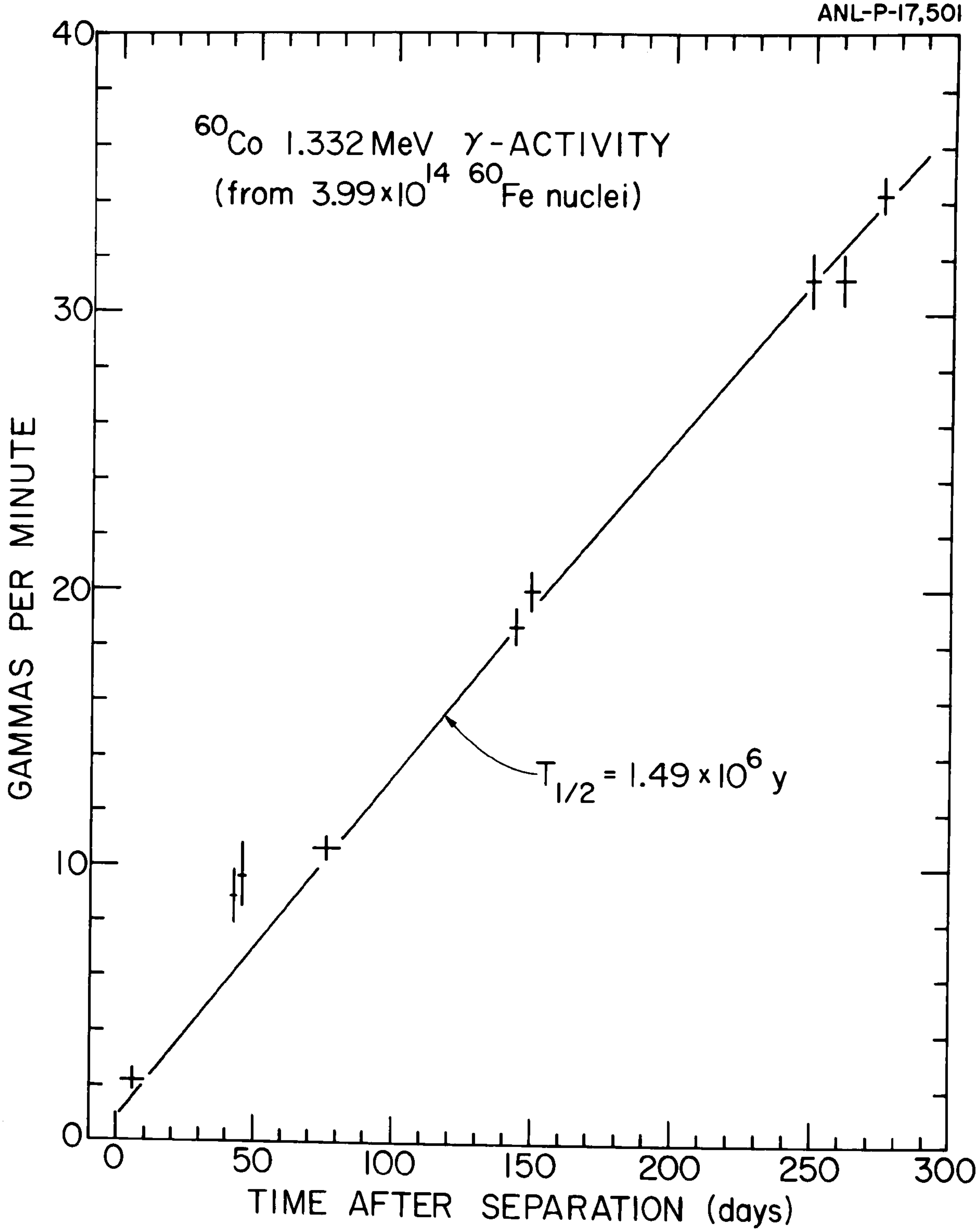

Figure II-15. Result of the γ-activity measurement. Plotted is the decay rate of ^{60}Co as a function of time after all ^{60}Co was chemically removed from the ^{60}Fe sample. The solid curve is a least squares fit of the function describing the feeding through the ^{60}Fe decay.

utilizing relatively short-lived radioisotopes, a number of systems were proposed with long-lived product nuclei. If one can find a geophysically well-defined environment for one of these latter systems, a neutrino flux integrated over geological time scales could be measured.

The ^{205}Tl-^{205}Pb system was proposed several years ago by Freedman et al.[2] at Argonne. The low threshold of the $^{205}Tl(\nu,e^-)^{205}Pb$ reaction (62 keV) makes it particularly sensitive to neutrinos from the dominant $p + p \rightarrow d + e^+ + \nu$ reaction [E_ν (max) = 420 keV]. Provided everything else is understood, one is faced with the analytical problem of measuring about 10^5 to 10^6 ^{205}Pb atoms in a typical sample material of several 100 kg from a suitable Tl ore.

We have recently started an investigation to study the detection of ^{205}Pb with the UNILAC accelerator at GSI, Darmstadt using the GSI spectrograph as the final detector. In two initial experiments at 2.3 GeV incident energy, we investigated the isotope and element separation between Pb and Tl ions with the following results: i) A suppression of $1{:}10^{14}$ between neighboring isotopes from the injection, accelerator and beam-line system alone. Time-of-flight and magnetic-rigidity measurement in the spectrograph provide for another factor of $\sim 10^3$. i) A nuclear charge separation of $Z/\Delta Z = 100$ between ^{205}Tl and ^{206}Pb, using the technique of a passive gas absorber and rest-energy measurement with the high-resolution spectrograph.

The major problem identified in our measurements is the very low efficiency from the positive ion source. Major improvements in ion source performance are needed in order to be able to perform a solar neutrino experiment where only a limited number of ^{205}Pb atoms will be available. Otherwise, the accelerator mass spectrometer described above seems capable of providing sufficient resolution and sensitivity for such a difficult measurement.

---

[2] M. Freedman et al., Science 193, 1117 (1976).

c. Development of a ^{10}Be Beam (W. Kutschera and K. E. Rehm)

The use of radioactive isotopes for ion beams allows one to study reactions inaccessible by other means. At present, only two radioistopes are in use on tandem accelerators, namely $^{3}H(T_{1/2} = 12.3$ yr) and $^{14}C(T_{1/2} = 5730$ yr). We plan to develop the technique for a beam of $^{10}Be(T_{1/2} = 1.6 \times 10^{6}$ yr) usable for unique nuclear-physics experiments. The amount of activity needed decreases with increasing half-life, thus reducing the radiation hazard. The relative ease with which ^{14}C beams are produced in several tandem laboratories (Brookhaven, Los Alamos, Munich, Orsay) clearly demonstrates this. The very long half-life of ^{10}Be fits nicely into this picture. However, as compared to ^{14}C there are two main problems to solve, namely the production of a source material sufficiently enriched in ^{10}Be and the low negative-ion yield. From previous experience with ^{9}Be beams we have estimated that with an enrichment of 0.1% of ^{10}Be in Be metal one should be able to produce a $^{10}Be^{4+}$ beam of 0.1 to 1 nA on target. Although low in intensity such a beam would allow one to study unusual reactions.

At present, we think that the most promising reaction to produce ^{10}Be for use in a sputter source is the $^{9}Be(d,p)^{10}Be$ reaction.

E. HYPERFINE SPECTROSCOPY AT THE TANDEM-LINAC

In addition to the programs described above, another main activity at the tandem-linac involves on-line laser spectroscopy. In this program, the optical hyperfine structure of radioactive atoms will be studied, in order to extract information on spins, moments, and the variation of charge radii for ground states and isomers. The laser system has been installed and tests of the cryogenic helium jet which transports the atoms into the interaction region are currently being pursued, using pure helium gas obtained from the boiloff of liquid helium. Work is also proceeding on coupling the laser system to the cryogenic helium jet.

a. Laser Spectroscopy of Radioactive Atoms (C. N. Davids, D. A. Lewis,* J. Kumar,† M. A. Finn,† G. Greenlees,† and S. L. Kaufman†)

Tests on the laser-beam transport system between the laser room and the cryogenic helium jet have been completed. It has been shown that the background from scattered laser light can be significantly reduced by using adjustable baffles to define the laser-beam path. Blackened razor blades mounted on micrometer movements are used as the collimating apertures. After passing through the laser-atom interaction region, the laser beam is intercepted by a piece of black glass tilted at Brewster's angle. This essentially eliminates reflections from a window which would occur if the beam were to be taken to an external beam dump.

Laser-light-scattering tests done with the helium jet in operation showed the presence of many showers of light-scattering centers. These seem to be associated with a CO_2 impurity in the helium gas, since the phenomenon did not occur when the temperature of the apparatus was raised above 200° K. In order to eliminate this problem, gas from liquid-helium boiloff is now used as the source of helium. Studies with the activities transported by this gas indicate that some may be in form of free atoms, although this can only be verified using laser fluorescence.

Additional helium-gas filtering will be provided by several canisters of molecular sieve kept at liquid N_2 temperature. The entire gas-handling system is constructed of stainless steel, and is baked out thoroughly under vacuum prior to operation.

---

*Iowa State University, Ames, Iowa.
†University of Minnesota, Minneapolis, Minnesota.

In order to further study the helium-jet transport system, a thin 1μCi source of ^{228}Th has been placed inside the target chamber. The transport of α-active ^{224}Ra and its daughters will enable these studies to be carried out without requiring accelerator beam time.

Several indications point to the fact that the helium flow in the present capillary tube is turbulent at liquid N_2 temperatures, while there is laminar flow at room temperature. A new target cell which will allow the interchanging of different diameter capillaries will be installed shortly. With this system and the use of the above-mentioned radioactive source, a whole range of operating conditions can be explored so that the helium-jet transport parameters can be optimized for high efficiency and reproducibility.

F. EQUIPMENT DEVELOPMENT AT THE TANDEM-LINAC FACILITY

The equipment development efforts are mainly concerned with two areas of activity. The first is concerned with the new experimental area for research with ATLAS. Equipment for ATLAS is well into the design stage with some construction already having been started. The apparatus to be built in the first construction phase includes: i) a large scattering facility, ii) a BGO sum-energy/multiplicity filter with a ring of Compton-suppressed Ge detectors, iii) the split-pole magnetic spectrograph to be moved from the tandem, iv) one atomic physics and two general-purpose beam lines. Design and construction of beam-line components is also well under way. An attempt is made to operate the beam transport system under computer control from the very beginning. This massive equipment development effort currently has high priority. An overview of the new target area is shown in Figure II-16.

The second area of activity has been directed towards the experimental facilities in the target area (II) after the linac booster. The equipment in area II is completed except for occasional upgrades to improve performance or to adjust to slightly-changing experimental requirements. It includes: i) the large 65" scattering chamber, with recent additions of a long flight path and an electrostatic deflection system, ii) the split-pole magnetic spectrograph with a sophisticated focal plane detector, iii) the gamma-ray facility with sum-spectrometer/multiplicity filter and accurate recoil-distance plunger, iv) the thin-wall neutron time-of-flight chamber, v) the electron spectrometer, vi) the cryogenic helium-jet/laser setup, vii) the small multi-purpose scattering chamber, and viii) a general-purpose beam line.

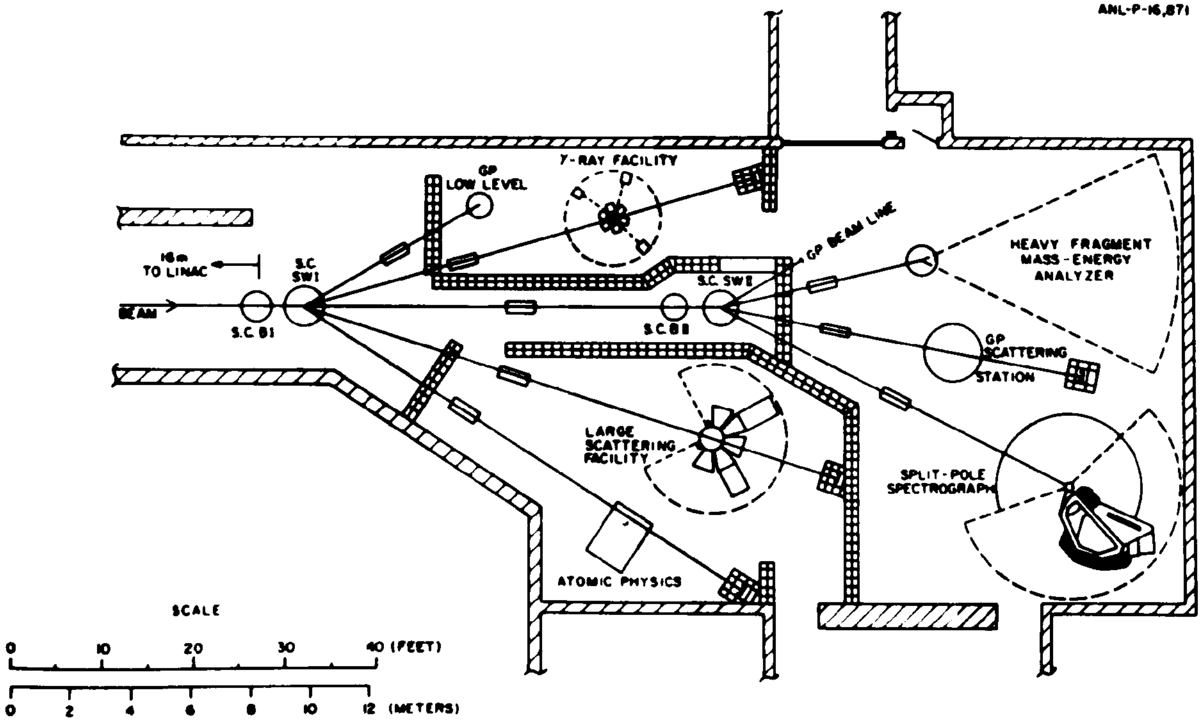

Figure II-16. Overview of new target area.

a. A Gamma-Ray Facility for ATLAS (R. V. F. Janssens, T. L. Khoo, D. C. Radford, U. Garg,* E. Funk,* J. Kolata,* and J. Mihelich*)

A proposal for a γ-ray facility for ATLAS to be constructed by a collaboration between the University of Notre Dame and ANL was recently submitted to DOE. This facility will ultimately consist of a BGO array with 56 elements and 10 Compton-suppressed Germanium spectrometers (CSS) arranged in two rings around the array (see Fig. II-17). The instrument will have a powerful impact on a large class of experiments in heavy-ion research. The internal BGO array serves not only as a γ-ray calorimeter but also provides a measure of the γ-ray multiplicity distribution characterizing each reaction burst. Each CSS will have excellent suppression over the whole energy range; for an incident photon of 1.2 MeV the expected peak/total ratio is > 0.66, a figure which is comparable to the best that has been achieved for any Compton-suppression system. With 10 CSS's of this type, double- and triple-coincidence spectra of excellent quality can be obtained in a reasonable time. The ability to select events within a specific range of sum-energy and multiplicity, together with the extreme sensitivity of the Compton-suppressed spectrometers, constitute a new tool for heavy-ion physics. Gamma-spectroscopic studies of very high quality and detail will be possible, promising significant advances in understanding nuclear structure as a function of spin and nuclear temperature. The instrument can also be used with ease in conjunction with charged-particle detectors located outside the BGO array. This will provide information toward a complete characterization of heavy-ion collision dynamics and reaction mechanisms. In fact, this instrument is ideally matched to the physics which can best be studied with ATLAS.

In order to establish the degree of interest in this device within the community of prospective users and to obtain input regarding specific needs, a one-day workshop was organized at Notre Dame on July 25, 1983. About 45 persons attended the meeting. The kind of physics possible using this type of device was addressed in invited talks as well as in discussions following these presentations. The technical aspects connected with the use of BGO detectors were discussed in contributions by representatives from Harshaw.

*University of Notre Dame, South Bend, Indiana.

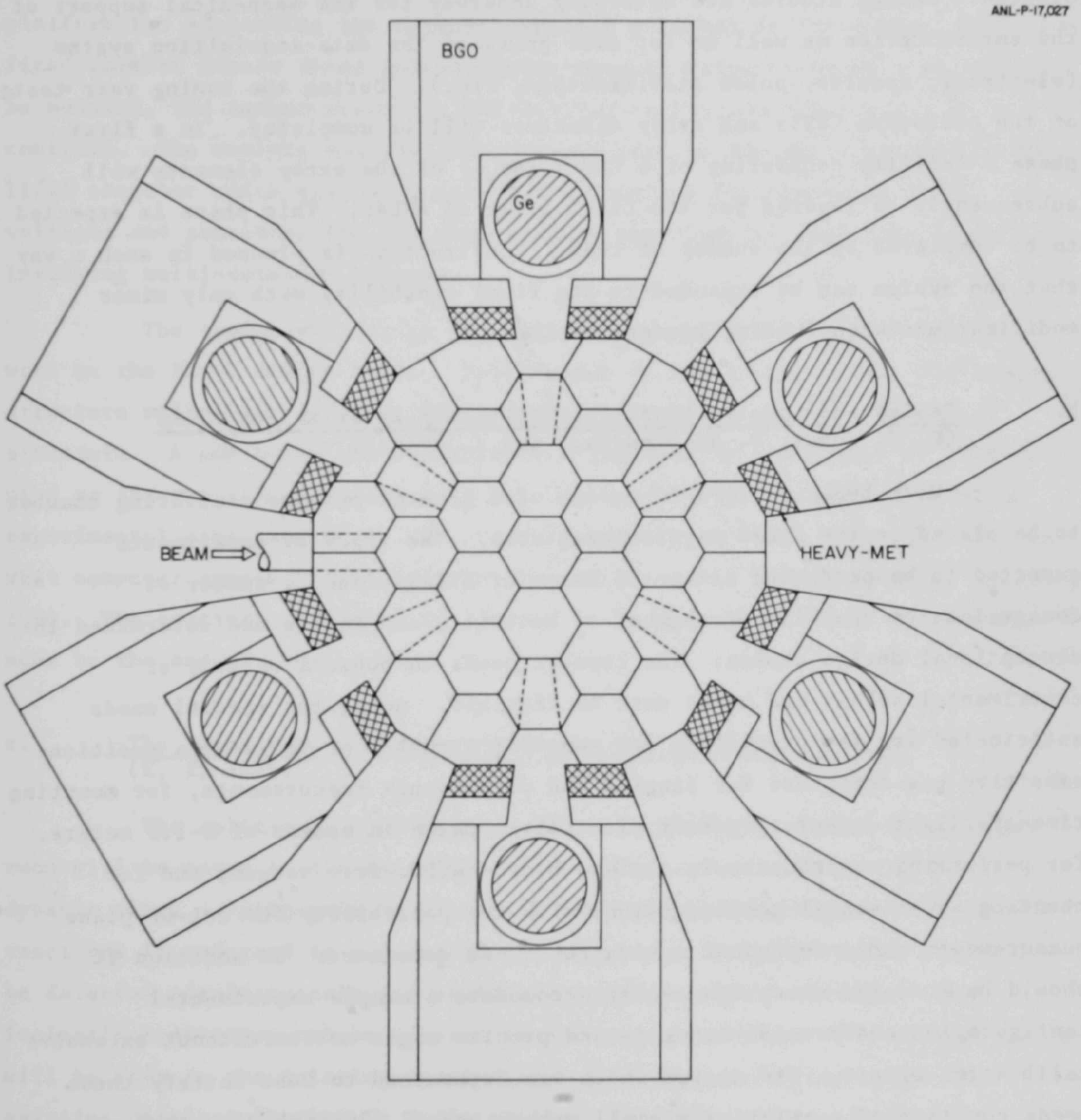

Figure II-17. Horizontal section of detector assembly. A central BGO array of 50 detectors is surrounded by two rings, each accommodating up to 6 Compton-suppressed Ge detectors, located 20° above and below the equatorial plane. The array can also be used on a stand-alone basis, with additional elements on the outermost ring, for a full complement of 56. The diameter of the BGO array is < 25 cm.

A major part of the afternoon was devoted to a group discussion on the design and use of the proposed facility.

A prototype CSS and prototype detectors for the array have been ordered. Design studies are currently underway for the mechanical support of the entire device as well as for some parts of the data-acquisition system (electronic modules, pulse stabilization, etc.). During the coming year tests of the prototype CSS's and array detectors will be completed. In a first phase a facility consisting of 6 CSS's and 14 of the array elements will subsequently be readied for the first beams of ATLAS. This phase is expected to be completed by the summer of 1985. Construction is planned in such a way that the system can be expanded to its final capability with only minor modifications when funding becomes available.

b. Design and Construction of a Scattering Facility for ATLAS (D. G. Kovar, S. J. Sanders,* and J. Falout)

Work began in 1983 on design of a general-purpose scattering chamber to be placed in the ATLAS experimental area. The types of experiments expected to be performed using the beams of ATLAS placed a number of constraints on the kind of chamber to be built, and in the end determined the conceptional design chosen. The chamber needs to house a variety of experimental setups and hence must be flexible. Among the special needs anticipated are the provisions for mounting a number of large-area position-sensitive gas detectors for singles and coincidence measurements, for mounting time-of-flight detector systems with flight paths in excess of 1-1.5 meters, for performing experiments in a clean hydro-carbon-free vacuum, and for mounting experimental configurations with the possibility for out-of-plane measurements and independent motion for these detectors. In addition it should be a design which can easily accomodate a simple experimental configuration and provide accurate and precise angle motion without extensive calibration effort. The design which was determined to best satisfy these needs consists of a relatively small vacuum vessel (36-inch diameter) where the upper half is rotatable by $\pm$ 45 degrees and the lower half is fixed. The

*Chemistry Division, ANL.

upper half has five large (12 in. x 12 in.) ports on which detectors or vacuum extension can be mounted and a sliding vacuum seal for the entrance-beam pipe to allow for rotation under vacuum. The upper chamber is attached to a large rotatable platform which provides the torque for rotation and serves as the platform for supporting the detector systems attached to the ports. The lower fixed chamber houses three independently movable rings on which detectors can be mounted, the target assembly, and various feedthrough cables and controls. The various motions and readouts will be accomplished using a PDP 11/23 computer which will also have the provisions for controlling the voltages and pressures for the more complex experimental configurations involving multi-detector systems.

The conceptual design work was completed in the fall of 1983 and work on the final design begun. Fabrication of the lower chamber and support structure will begin in early 1984, to be followed by that for the upper structure. A gun mount was obtained from the Navy in the summer of 1983 to be used as the rotation platform. It has been modified, located in the ATLAS experimental area, and installed and aligned early in 1984. The decision on what computer system to purchase has been made and it will be ordered early in 1984. The scattering chamber is planned to be operational in a rudimentary mode by the end of 1984.

c. The Split-Pole Spectrograph in the New ATLAS Target Area (K. E. Rehm)

The split-pole spectrograph which is presently in the West Target room will be moved to the new ATLAS experimental area. Due to its large dynamic range a split-pole spectrograph has several advantages for heavy-ion reactions if compared to e.g. a Q3D spectrograph. Several charge states can be detected simultaneously and excitation energies from elastic to deep inelastic scattering can be covered in one magnet setting. The changes which will be made to the existing spectrograph include a modification of the existing detector chamber to fully utilize the large bending radii, an upgrade of the vacuum system, and a new power supply.

The foundation for the magnet has been completed and work on mounting the rails has been started. The schedule is to have the magnetic spectrograph ready for taking data in late 1984.

d. Superconducting Solenoid Lens Electron Spectrometer (P. J. Daly,* Z. Grabowski,*, R. Nielsen, R. V. F. Janssens, T. L. Khoo and J. Worthington)

Work has continued on the construction of the Purdue superconducting electron spectrometer to be installed at the linac. The beam-line has been assembled and the beam transport properties have been measured. Studies of the problems associated with background in the electron spectra are currently underway with a Gerholm-type normal-conducting electron-lens spectrometer on loan from Oak Ridge National Laboratory. Meanwhile, the design and construction of the target chamber and the beam dump for the superconducting lens have been completed. The design of the detector cryostat is in progress.

*Purdue University, W. Lafayette, Indiana.

e. Development of a Timing Detector for the Split-Pole Magnetic Spectrograph (K. E. Rehm and A. van den Berg, L. L. Lee,* and G. S. F. Stephans)

In order to determine Q-value, nuclear-charge Z, mass M and atomic-charge q for the reaction products from a binary reaction, four quantities have to be measured. The focal-plane detector of the spectrograph so far allows the measurement of three quantities (ΔE, E_{total}, $B\rho$). This can result in ambiguities in the mass determination for some cases. A measurement of the time-of-flight through the spectrograph will provide the fourth parameter, which will allow the unambiguous identification of reaction products over a large mass and Z-range. A parallel-plate avalanche detector (75 cm long and 3 cm high) was developed which can be mounted in front of the position-sensitive ionization chamber. The detector has been tested with ^{4}He, ^{16}O, ^{32}S and ^{58}Ni ions. The rise time of the fast signal was 2 nsec and the intrinsic time resolution observed for ^{58}Ni ions was 300 psec. Thus a mass determination of reaction products in the mass 100 region seems possible.

*State University of New York, Stony Brook, NY.

f. Development Work on Gas Detectors (D. G. Kovar, I. Dorion, E. Grote, H. Ikezoe,* J. J. Kolata,† K. Lesko, and G. S. F. Stephans)

A low-pressure multi-wire proportional counter has been constructed for use in time-of-flight measurements requiring time resolutions of the order of Δt(FWHM) = 100-200 picoseconds. In measurements of evaporation residues and fission fragments produced in fusion reactions, detector systems which provide mass or Z identification in addition to the energy or velocity are necessary in most instances. To do this, thin start detectors (for time-of-flight measurements) or dE/dx detectors (for determining Z) are needed in order to provide the identification without stopping the low-energy reaction products. The low-pressure MWPC is ideal for this purpose since it operates at low pressures (1-3 torr), necessitates only thin foils (30-40 gm/cm^2) for the gas containment, and potentially can provide good timing resolutions with high efficiency. A small prototype MWPC was constructed and tested using a ^{28}Si beam from the Superconducting Linac. In this initial test the detector worked well, but the timing resolution was only Δt(FWHM) = 350 picoseconds. Further work will be done in the coming year to improve the resolution and to incorporate the detector into the time-of-flight system used in research. In the course of construction and testing of the detector, a gas-handling system for low pressures was constructed, the techniques for producing thin foils and stretching thin wires were developed, and work was begun on the construction of a vacuum chamber for testing gas detectors. In the coming year work will begin on the fabrication of gas detectors for use on the ATLAS scattering chamber which is presently being constructed.

g. A New Foil Stretcher for Recoil-Distance Measurements (D. C. Radford)

The recoil-distance method (RDM), or "plunger" technique, is widely applied in the measurement of lifetimes of excited nuclear levels in the range 1 ps $< \tau <$ 1 ns. The excited nucleus is produced in a thin, flat target and recoils into vacuum. A flat "stopper" is placed a distance D down-beam from the target. If the recoil velocity is sufficiently high, the Doppler shift of the γ-rays emitted from the moving nuclei allows us to resolve them from those emitted after the nucleus has come to rest. Thus, by varying the distance D, one can trace out the decay curve of the level to find its mean life.

*Japan Atomic Energy Research Institute, Tokai-Mura, Japan.

South Bend, IN.

Accurate measurements of short lifetimes, say $\tau < 10$ ps, require very short target-stopper separations, and therefore very flat targets and stoppers.

A new foil stretcher for the production of RDM targets and stopper foils has recently been developed at Argonne. The technique relies on a compression of an "O"-ring in contact with the foil to be stretched. As the "O"-ring is compressed, this foil gets drawn down tight across a small tube of aluminum, the end of which has been optically polished to give a flat, clean stretching surface. These stretchers have been used in an experiment at Argonne in the measurement of mean lives in ^{147}Gd and performed completely satisfactorily. The new stretchers are considered to be superior to the old ones in that they make it much easier to successfully and reliably stretch thin foils to an acceptable flatness. Using two gold foils and the new stretcher, a minimum distance of 3 μm (0.12 mils) before electrical contact has been obtained.

h. Nuclear Target Making and Development (G. W. Klimczak, V. E. Krohn and G. E. Thomas)

The Physics Division operates a facility which produces or arranges for the production of thin targets for charged-particle experiments, principally at the Tandem-Linac and Dynamitron accelerators. In addition, evaporated films are occasionally prepared for other experimental purposes. These services are available to the Physics Division and other divisions of the Laboratory and sometimes to other scientific institutions. A major activity at this facility is a continuing effort to develop new target-making methods, to acquire the ability to make use of new techniques developed elsewhere, and to do research leading to a better understanding of the factors involved in target making.

Last year the elements, isotopes and compounds prepared were Au, Al, $Ba^{37}Cl_2$, Bi, ^{11,12}B, C, Cu, ^{40}Ca, CaF, Ge, ^{155,156,157}Gd, LiH, ^{6,7}LiF, LiI, Li_2SO_4, $^{Nat,\ 206,207,208}$Pb, Pt, ^{112,114,116,118,120,122,124}Sn, ^{Nat,28,30}Si, ^{144}Sm, ZnS, and ^{90,92,96}Zr. Many of the above materials were included in "sandwich" targets. Of particular interest in this area were sandwiches of ^{155,156,157}Gd, Au, and Pb where about 1 $\mu g/cm^2$ of Au was included to produce an improved bond between the Gd and Pb which tend to separate when used without the Au.

The computerized target-storage system with turbo-pumps is complete except for the software, the relatively clean evaporator system which uses a cryo-pump has been used successfully, and the sputter source has been installed in a system where we expect it to be available without installing and removing it each time it is used. Also, we have started a program to make jigs and fixtures to improve the ease and precision of locating glass slides and target frames for evaporations and to increase the number of slides and/or frames which can be coated in a single evaporation.

Plans for the future include comparison of the quality of targets and our ability to float self-supporting films when the films have been prepared by sputtering, evaporation in our cryo-pumped system, or evaporation in a system using an oil diffusion pump.

i. Computer Facilities (Lester C. Welch)

VAX 780

The VAX 780 has been upgraded to provide better performance by (1) adding 2MB of memory to bring the total to 4MB, (2) adding a 125 ips 6250 bpi tape drive, (3) adding a floating-point accelerator, and (4) adding an additional communications board to provide 16 more terminal lines. In addition, the Physics Division VAX was tied into the site-wide NJE network. It is anticipated that within the next year an additional printer will be added to provide inexpensive listings. The present printer/plotter will then be used mainly for plots and backup printing capability.

Data Acquisition

A project to satisfy the data-acquisition requirements of ATLAS has been implemented. The system called DAPHNE (Data Acquisition by Parallel Histogramming and NEtworking) will consist of three major hardware components and considerable software support. The hardware will consist of a CAMAC system, a multibus-based front-end processor utilizing several single-board computers (SBC's) in a loosely-coupled parallel mode and a super-mini computer. It is proposed that the super-mini computer be a VAX 750 to maintain compatibility within the division. The CAMAC crate will be governed by the VAX via an RS232 crate controller through which a programmable auxilliary crate controller (AUX) can be downloaded. The VAX-CAMAC communications link has been tested and the cross-compiler for the AUX also has been written. The AUX will be the Event Handler as designed by David Hensley of ORNL and more thorough testing of the downloading process will be done upon receipt of an Event Handler.

The CAMAC-MULTIBUS data link will be from a CAMAC FIFO module (which is being filled by the Event Handler) over parallel twisted pairs differentially driven to a parallel input port of one of the Multibus single-board computers. This part of the system is currently being designed and built by the Electronics Division.

The MULTIBUS-VAX communications will be via a DMA board on the UNIBUS of the VAX. The hardware board for the Multibus has been built and the UNIBUS board was commercially available. The software drivers, to function under the VAX operating system VMS, are presently being written. The MULTIBUS-VAX communications link will also be used to download the SBC's (most probably based on the 80286/80287 Intel microprocessor chips) from cross software on the VAX.

Considerable support software on the VAX has been written. Histograms can be created, displayed, plotted, printed, saved and recalled. Interactive definition of CAMAC structure is implemented. Many of the utility routines which allow changing or deleting data-acquisition parameters have been implemented.

Extensive use has been made of the programming tools available in VMS. The Command Language Interpreter (CLI) has considerably eased the user-software interface. Global Sections has greatly eased the process-process communication and has greatly aided modularity.

It is anticipated that DAPHNE will be available for replay analysis in the near future so that considerable testing and user reaction can be obtained before on-line usage.

III. THEORETICAL NUCLEAR PHYSICS

Introduction

The principal areas of research in the nuclear theory program are:

1. Nuclear forces and sub-nucleon degrees of freedom.
2. Variational calculations of finite many-body systems.
3. Nuclear shell theory and nuclear structure.
4. Intermediate energy physics with pions, electrons and nucleons.
5. Heavy-ion interactions.

In 1984 much progress was made in including the delta degree of freedom in nucleon-nucleon potentials. This led to an important result by providing a means of estimating the density of pions in nuclei as a function of mass number, thus providing an alternative interpretation of the results of deep-inelastic lepton scattering (EMC effect) in terms of scattering from pions as well as nucleons. Techniques of variational many-body calculations were also extended in treating ^{3,4}He droplets and in studies of binding energy of hypernuclei. A widely-attended Symposium on Delta-Nucleus Dynamics was held in May. Recent results and plans for the future in the five main areas are contained in sections A-E, and other theoretical work is given in section F.

A. NUCLEAR FORCES AND SUBNUCLEON DEGREES OF FREEDOM

(F. Coester, B. D. Day, M. J. King, T.-S. H. Lee, J. Parmentola, R. Wiringa, and collaborators from other institutions)

Much of our work is motivated by three central questions. (1) What should be the active degrees of freedom? (2) What is the Hamiltonian that governs the nuclear many-body dynamics? (3) What can electromagnetic probes reveal about short-distance nuclear structure?

For the conventional nuclear theory which assumes that nucleons are the only active degrees of freedom it is not required that two-body forces alone are sufficient, but it is essential that the same Hamiltonian account for both light and heavy nuclei and that the importance of the n-body forces decrease rapidly with increasing n. We have previously established that two-body forces alone cannot account for the properties of nuclear matter. During 1982-83 we investigated the effects of several three-body interactions in ^3H, ^3He, ^4He and nuclear matter. Inclusion of these three-body forces is a marked improvement, but a discrepancy remained. We have shown in a preliminary calculation that relativistic effects have the right sign and the right magnitude to remove this discrepancy.

A promising extension of the conventional theory includes the Δ isobar among the active degrees of freedom. This step may drastically reduce the need for explicit three-body forces. We have constructed two NN potentials including isobar degrees of freedom with emphasis on different objectives: (1) A realistic NN potential with Δ degrees of freedom that gives a high quality fit to two-body data below 400 MeV and can be readily used in nuclear structure calculations. (2) A realistic meson exchange potential including Δ, N^* and π degrees of freedom that gives a good fit to two-body data < 2 GeV and is designed primarily for applications in medium energy pion-nucleus physics. These applications are described in Sec. D.

Evidence for subnucleon degrees of freedom from spectroscopic and elastic scattering data is always indirect. In contrast inclusive deep inelastic scattering reveals directly the charge and momentum carrying constituents; deep inelastic electron scattering provided the definitive evidence for the existence of quarks and glue. Recent data obtained by the European Muon Collaboration (EMC) for deep inelastic scattering of muons from iron and deuterium are thus of prime importance. We examined whether these data can be explained in terms of deep inelastic scattering from mesons responsible for nuclear binding. We found that for small values of the Bjorken scaling variable x, a quantitative agreement with the EMC data cannot be achieved in this manner. We speculate that a quantitative fit to the EMC data for small x requires an "intrinsic" enhancement of the nucleon structure function as well as scattering from mesons.

The role of quark degrees of freedom in nuclear theory depends critically on the quark distribution within the nucleon. The assumption of a "little" quark bag surrounded by a pion (or $q\bar{q}$) cloud leaves room for much of the conventional meson-nucleon dynamics. However, in such models the pion cloud strongly contributes to the structure of the nucleon and an accurate solution of the one-nucleon problem is a prerequisite for further applications. We have been investigating properties of static chiral bag models in the strong coupling approximation.

Constituent quark models with QCD based potentials also predict a small radius of the constituent quark distribution. Such models account well for the spectroscopy of single hadrons, but in their present form they do not provide a satisfactory multi-hadron dynamics. Along these lines we are working on the development of models designed to include meson creation and hadron-hadron interactions in a satisfactory manner.

Much of the quantitative information that will determine the success or failure of competing models will come from electromagnetic probes. Observed quantities are directly related to matrix elements of the electric charge and current densities. Probes of short range features inevitably involve relativistic effects. A valid interpretation requires mutually consistent representations of the current operators and the target wave functions. Work is in progress on the construction of relativistic current operators that are consistent with relativistic particle models.

a. Variational Calculations of Resonant States in ^{4}He
(R. B. Wiringa, J. Carlson* and V. R. Pandharipande†)

A modified R-matrix method has been developed which allows microscopic calculations of nucleon-nucleus scattering at low energy. The scattering problem is reformulated as an eigenvalue problem in a finite region with a fixed boundary. The energy, E, of an excited state in this region can be related to the phase shift, δ, and as the boundary is varied $\delta(E)$ can be mapped out. The $\delta(E)$ can then be examined for resonant behavior and excited state energies and widths extracted. The eigenvalue problem can be studied with any numerical method suitable for few-body systems, e.g. Green's Function Monte Carlo, Faddeev or variational.

We have used the variational Monte Carlo approach with this procedure to study low-energy t-p scattering in the region of the 0^+, 0^- and 2^- T=0 resonances in ^{4}He. A realistic Hamiltonian containing the Urbana v_{14} two-nucleon and model V three-nucleon interactions was used, but the Coulomb interaction was neglected. This Hamiltonian gave ground state energies for ^{3}H and ^{4}He of $-8.1\pm.1$ and $-29.9\pm.4$ MeV, respectively. A variational wave function was constructed as a few-parameter excitation operator of appropriate J, P and T acting on the variational ground state. The parameters of the excitation operator were varied to minimize the energy (calculated with Monte Carlo integrations) for a fixed boundary. Seven different boundaries were used in both the 0^- and 2^- cases to map out $\delta(E)$, and resonant behavior, as

*New York University, New York, New York.
†University of Illinois, Urbana, Illinois.

indicated by a rapid increase in δ(E) over a small region in E, was observed in both, as indicated in Fig. III-1. Resonances were indicated at -6.5±.5 and -4.0±.5 MeV for the 0^- and 2^- cases respectively, which can be compared to -7.4 and -6.4 MeV for the Coulomb corrected experimental (i.e. R-matrix fit) values. The variational quantities are of course only upper bounds. The widths of the resonances, as indicated by the slope of δ(E) at the resonance, are poorly determined due to Monte Carlo sampling errors: 1±1 MeV for the 0^- state and 2.5±1 MeV for the 2^- state. With the Coulomb force neglected, the 0^+ state is slightly bound. It may be calculated with a similar procedure, making sure the variational excited state is orthogonal to the ground state. The computed value was -8.6±.4 MeV, compared to the Coulomb corrected value of -8.5 MeV. A paper reporting this work has been accepted for publication in Nuclear Physics A.

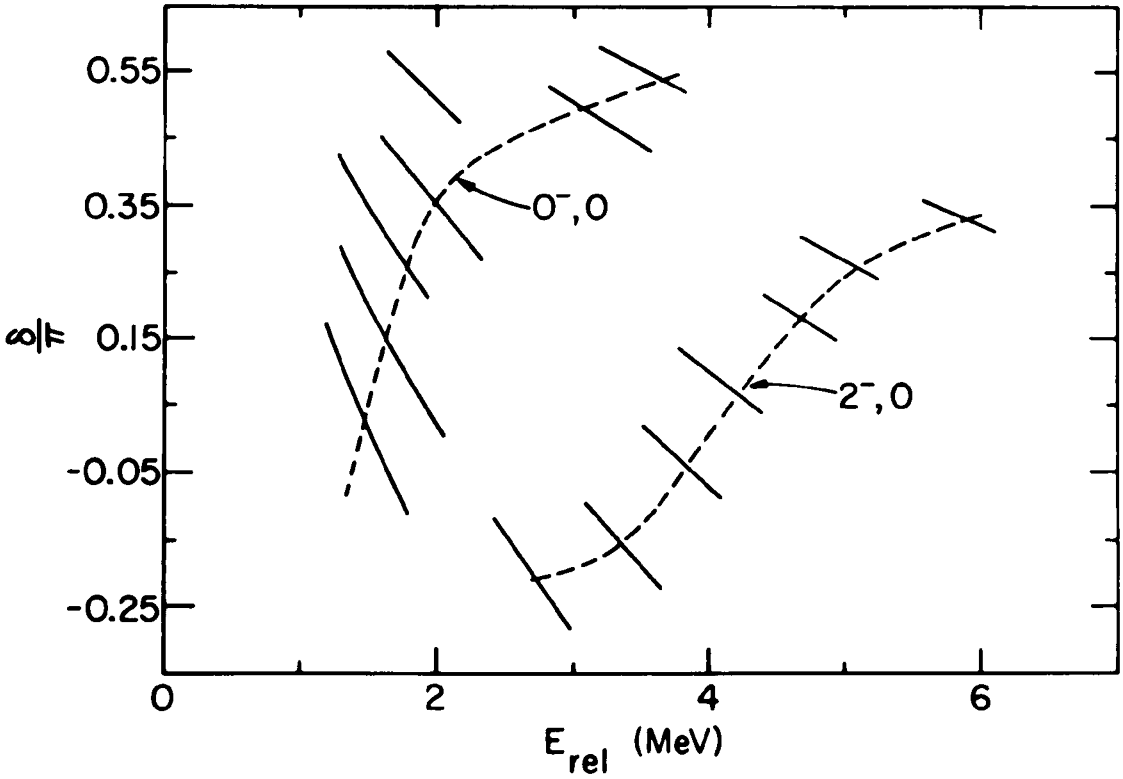

Figure III-1. Calculated values of δ(E) with their Monte Carlo sampling errors are shown by solid lines, and the fitted δ(E) by dashed lines.

b. Studies of Three-Body Forces in Light Nuclei (R. B. Wiringa, J. L. Friar*, B. F. Gibson*, and G. L. Payne†)

The effect of three-body forces in nuclear systems has received considerable attention in the last few years. Conventional two-nucleon potentials that fit two-body scattering data underbind light nuclei while overbinding nuclear matter. Both theoretically and empirically we expect three-body forces to be a necessary ingredient for obtaining a quantitative understanding of nuclear saturation.

In work reported here last year, Carlson, Pandharipande and Wiringa (CPW) showed that reasonable three-body potentials, such as the model of the Tucson group, could contribute ~1 MeV additional binding to the triton and ~6 MeV to the alpha particle. The many-body technique used was the variational Monte Carlo (VMC) approach where Monte Carlo sampling with a variational trial wave function to guide a random walk is used to obtain an upper bound to the ground state energy. The advantages of the technique include the ability, given a wave function, to take expectation values of arbitrary operators, such as a full two- plus three-body Hamiltonian, without the partial wave expansions that plague Faddeev calculations. It is also possible to make good four-body calculations, where the generalized Faddeev calculations do not seem to work well. The chief disadvantage is the difficulty of finding the best trial wave function (the one with the lowest energy) among many when Monte Carlo sampling errors are present and different random walks are followed.

While the VMC calculations give upper bounds indicating significant additional binding from the Tucson three-body potential, two momentum-space Faddeev calculations were reported last year by the Purdue and Bochum groups that found essentially no effect in the triton. To investigate this discrepancy, we have used conventional 5-channel configuration-space Faddeev wave functions as input to the Monte Carlo integration routine and taken expectation values for the triton for a variety of Hamiltonians. These include the Reid Soft Core, Argonne-v_{14} and Super Soft Core (C) two-nucleon potentials and Tucson and Urbana model V three-nucleon potentials. The results are in substantial agreement with the earlier VMC results; e.g. with Argonne-v_{14} the Tucson force adds 1.1 MeV additional binding. Meanwhile the

*Los Alamos National Laboratory, Los Alamos, New Mexico.
†University of Iowa, Iowa City, Iowa.

Bochum group has concluded that their calculation has not converged and they are unlikely to be able to make any definitive statement about the three-body force contribution in the triton.

One result of these studies, however, is the discovery that the Faddeev wave functions are better (a few % more binding energy) than the variational ones used by CPW. We are trying to understand how to improve the variational wave functions, since they are more readily useable in the four-body calculations and our empirical deductions about the nature of the three-body force will rely heavily on the ground state properties of both these systems. Since the three-body potential is giving more binding, the best wave function for the full Hamiltonian should be "sucked in" compared to the Faddeev wave function that is generated from the two-body potential alone. (Faddeev wave functions including the effect of three-body forces have not yet been generated.) Thus we are also looking at simple variations on the Faddeev wave functions that would embody this effect (which will show up more in a change of the charge radius than in additional binding energy). To do this we are computing the difference in energy between slightly different wave functions, which can be done on a much finer level than the Monte Carlo variances associated with the absolute energy. This work was reported at the International Workshop on the Three-Nucleon Force, Bochum, West Germany, August 1983, and a paper has recently been submitted for publication.

c. Relativistic Effects in the Binding Energy of Few-Body Nuclei (F. Coester and R. B. Wiringa)

We have examined the consequences of Poincaré invariance for binding energy calculations of few-body nuclei. Previously attempts have been made to simultaneously fit the binding energy of 2-, 3-, 4-body nuclei and nuclear matter. These attempts did not succeed. We have shown that relativistic effects have the order of magnitude and the sign required to remove this discrepancy. This work was reported at the 10th International Conference on Few-Body Problems in Physics, August 1983.

d. Nucleon-Nucleon Potentials with Isobars (R. B. Wiringa, R. A. Smith,* and T. Ainsworth†)

Two NN potential models designated Argonne-v_{28} and Argonne-v_{28q} that include NN↔NΔ and NN↔ΔΔ transitions have been constructed. The intermediate-range attraction observed in NN scattering can be attributed largely to two-pion-exchange processes with possible isobars in the intermediate state. Part of these processes behaves like a twice-iterated one-pion-exchange potential with πNΔ coupling. The description of many physical processes, where isobars and pions are believed to play an important role, will benefit greatly from reliable NΔ transition models with good fits to the scattering data.

In present work, the isobar is treated as a stable particle. A one-pion-exchange potential, containing πNN, πNΔ, and πΔΔ couplings is supplemented by phenomenological intermediate and short-range terms. The NN↔NN part is taken in a v_{14} form, i.e., fourteen operator components, and with the transitions added, a total of 28 operators appear in the full potentials. The coupled-channel Schrödinger equation is solved for the deuteron and all $J<5$ partial waves in the NN channel for a variety of energies up to 400 MeV. This includes up to twelve coupled channels in the $^3F_4$-$^3H_4$ component. The phenomenological part of the potentials is adjusted to obtain good fits to np phase shifts. A direct comparison to 1760 np data points in the range 5-330 MeV shows excellent fits with a χ^2/point of ~1.7. Deuteron properties are also well reproduced.

As an exercise in learning how to efficiently search in a large parameter space for the best fit, the code was also used to construct a conventional NN potential, Argonne-v_{14}. This potential was built with the same structure as the Urbana-v_{14} model, for which reliable variational many-body calculations have been developed. It has already been used in a study of phenomenological three-body forces. It also gives an excellent fit to data, and has a similar structure to the v_{28} model to facilitate comparison of results from many-body calculations. A paper describing this work will be published in Physical Review C.

*Texas A & M University, College Station, Texas.
†University of Arizona, Tucson, Arizona.

The v_{28} models are now being used as input to light nuclei and nuclear matter calculations. The presence of explicit isobars in many-body clusters simulates many-body forces that are omitted when conventional NN potentials are used. Such models may provide a solution to the present difficulty in obtaining reasonable saturation properties for nuclear systems with conventional potentials. The representation of the intermediate range attraction in NN interaction as an effect of $\pi N\Delta$ coupling also makes the v_{28} models particularly appropriate for studying the pion number density in nuclei (see item A.g.).

e. Coupled Cluster Calculations with the Argonne v_{14} Potential (B. D. Day and R. B. Wiringa)

To calculate the binding energy of nuclear matter, we have earlier developed a procedure for accurately solving the coupled-cluster equations, including both two- and three-body correlations. The method requires, as input, matrix elements of the two-body potential in momentum space. Until now, this has restricted use of the method to potentials that can be analytically transformed to momentum space. We have developed a numerical method for transforming coordinate-space potentials, such as Argonne v_{14}, to momentum space. The method is sufficiently fast to be used in time-consuming three-body calculations. It is now being incorporated into the programs for coupled-cluster calculations. This will permit coupled cluster calculations for a much wider class of two-body potentials, and hence a more extensive comparison of the coupled-cluster method with the variational method.

f. Momentum Distribution in Nuclear Matter (B. D. Day)

The one-nucleon momentum distribution n(k) in nuclei is of great interest for several reasons. It is sensitive to short-range two-body correlations. It is needed in calculations of the structure functions of nuclei, which have recently been measured by deep inelastic muon scattering. It also permits a comparison among different calculational methods, e.g., coupled-cluster and variational methods. The momentum distribution for nuclear matter in the two-body coupled cluster approximation has been calculated. A single-particle spectrum with a gap at the Fermi surface was used. Hence the behavior of n(k) at the Fermi surface is not accurate. Away from the Fermi surface, and for calculation of average properties such as kinetic energy, the calculated n(k) is expected to be accurate to roughly 10%. Calculations have been made for the Paris, Reid, v_6(Reid), and v_2 potentials. Paris and Reid give excellent fits to two-body data, while v_6 (Reid) and v_2 are simpler potentials used for comparison with variational results (not yet available for Paris and Reid). The comparison between coupled cluster and variational results shows good agreement for v_2 and v_6 (Reid). A report is being prepared for publication.

g. Calculations of Pion Excess in Nuclei (R. B. Wiringa, B. L. Friman*, and V. R. Pandharipande†)

Nucleons are surrounded by pion fields, so the expectation value of the pion number operator in the state describing an isolated nucleon, $\langle n^\pi \rangle_N$, is nonzero. When A nucleons are brought together to form a nucleus, they interact by exchanging pions, and $\langle n^\pi \rangle_A$ for the nucleus is greater than $A\langle n^\pi \rangle_N$. The pion excess, $\langle \delta n^\pi \rangle_A = \langle n^\pi \rangle_A - A\langle n^\pi \rangle_N$, contributes to the exchange currents seen in electromagnetic scattering from nuclei, and helps explain the differences observed in deep-inelastic lepton scattering from ^{56}Fe and ^2H. We have estimated $\langle \delta n^\pi \rangle_A$ by means of a many-body calculations using an appropriate operator.

In conventional nuclear many-body theory the pion degrees of freedom are eliminated in favor of a static one-pion-exchange potential, V^π_{ij}. The many-body Schrödinger equation is solved for a Hamiltonian containing V^π_{ij} to obtain the ground state $|A\rangle$ for a system of A nucleons. The analogous static two-body operator for the pion excess is $\delta n^\pi_{ij}(k) = -V^\pi_{ij}(k)/(\mu^2+k^2)^{1/2}$; the expectation value of this operator taken with the state $|A\rangle$ gives the estimate of pion excess. Because the isobar plays an important role in πN interaction, the Argonne v_{28} potential with explicit isobar degrees of freedom (see item A.d.) is used as the Hamiltonian for obtaining the state $|A\rangle$. This approach should get the bulk of the contribution to $\langle \delta n^\pi \rangle_A$ coming from one- and two-pion exchange, plus the quenching effect of short-range NN repulsion consistent with low-energy NN scattering. Since $|A\rangle$ contains the effect of V^π_{ij} to all orders, we obtain more than just a perturbation estimate.

*University of Åbo, Åbo, Finland.
†University of Illinois, Urbana, Illinois.

The state $|A\rangle$ for ^2H is just the deuteron wave function, while for nuclear matter it is obtained variationally using Fermi-hypernetted-chain and single-operator-chain techniques. The local density approximation is then used to estimate $\langle \delta n^{\pi}(k) \rangle$ in finite nuclei from the nuclear matter results. The computed pion excess/nucleon for various nuclei are: 0.024 for ^2H, 0.11 for ^{27}Al, 0.12 for ^{56}Fe and 0.14 for ^{208}Pb. The momentum distribution of the pion excess is shown in Fig. III-2. This work has been published in Phys. Rev. Lett. 51, 763 (1983). The results are also used as input to the study of deep inelastic lepton scattering (see item III.A.h.).

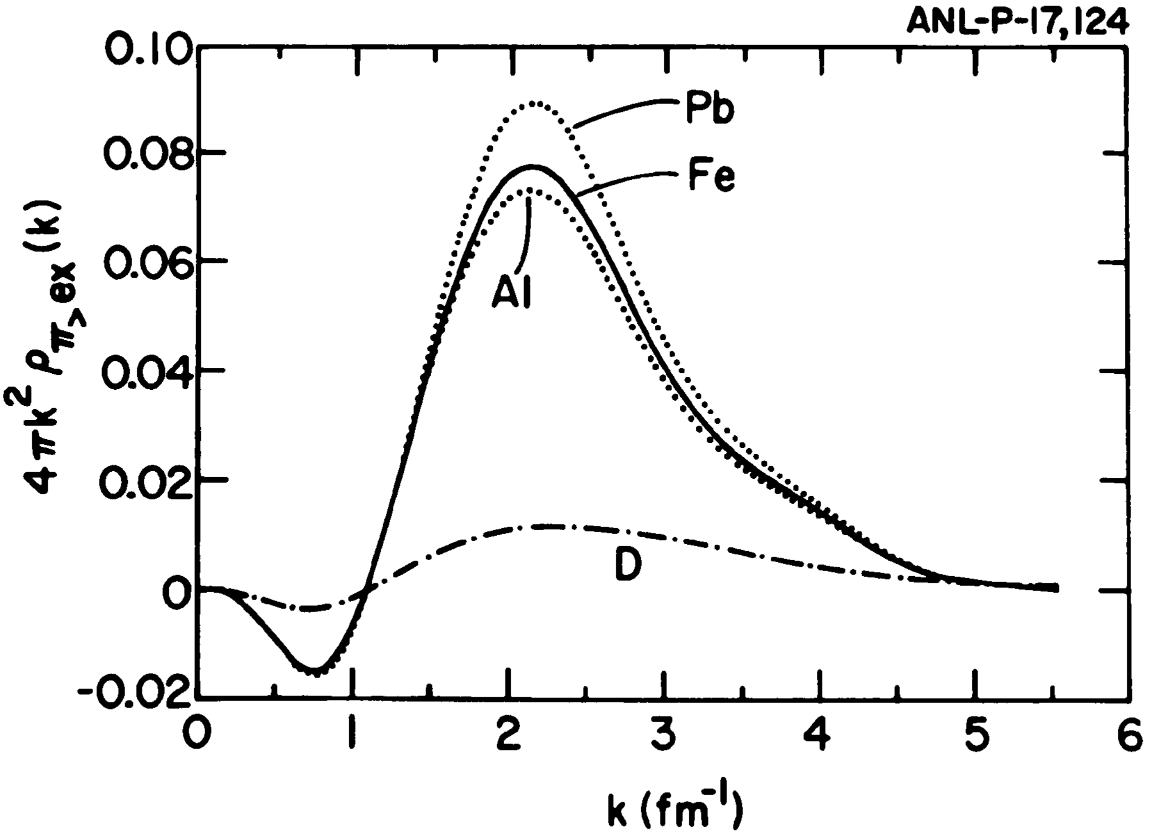

Figure III-2. Momentum distribution of the pion excess in various nuclei.

h. Pion Density in Nuclei and Deep Inelastic Lepton Scattering
(E. L. Berger,* F. Coester and R. B. Wiringa)

Recent data from the European muon collaboration[1] (EMC) indicate that the quark densities in a high A nucleus differ significantly from those measured in the free nucleon case. We examined whether this effect can be explained in terms of deep inelastic scattering from mesons responsible for nuclear binding. There are three main ingredients in the approach we study. First, we assume that nuclei are bound systems of nucleons and mesons. Second, we assume that the deep-inelastic structure functions of these nucleons and mesons are unaffected by the nuclear medium; in our calculations we employ structure functions measured on isolated nucleons and pions. Third, we retain the usual assumption that nucleons contribute incoherently to the structure function of the nucleus, and we add the same incoherence assumption for the mesons. Although features of the data are reproduced qualitatively, we are unable to approach a quantitative description of the magnitude of the experimental effect at small x ($x = Q^2/2M\nu$ is the Bjorken scaling parameter) unless we postulate an enhanced pion density of about 0.4 extra pions per nucleon (roughly three times that provided by conventional nuclear models), and/or make assumptions about the small-x behavior of the meson structure function which are inconsistent with available data. The slope of the ratio of structure functions vs. x is reproduced easily in the range of $0.05 < x < 0.6$. While improvement in the treatment of the nuclear wave function may produce quantitative agreement with the data for $x > .3$, the disagreement for small x is insensitive to such improvements. We speculate that a quantitative fit to the EMC data for small x requires an "intrinsic" enhancement of the nucleon structure function due to the nuclear medium as well as scattering from the mesons associated with binding. This work was reported in an invited paper at the "Third International Conference on Recent Progress in Many Body Theories" at Altenberg, West Germany in August 1983. An article on this work has been published in Physical Review D 29, 398 (1984).

Recent experiments at SLAC[2] show little enhancement at small x. Improved calculations with our model give good agreemnt with these new data for Al, Fe and Au.

---

*High Energy Physics Division, ANL.
[1]J. J. Aubert et al., Phys. Lett. 123, 275 (1983).
[2]R. G. Arnold et al., Phys. Rev. Lett. 52, 727 (1984).

i. Many-Body Forces in Directly Interacting Systems (T. Biswas*, F. Rohrlich* and M. King†)

The conventional formulation of classical relativistic Hamiltonian constraint dynamics of N interacting particles assumes N constraints which are required to satisfy an Abelian Poisson-bracket algebra. This requirement imposes restrictions on the permitted interactions, resulting in many-body forces. These are difficult to compute for given two-body forces. We propose a perturbative method for this purpose, which is symmetric in the particles. It requires Poincaré-invariant integration, which is discussed in detail. An example is solved explicitly. An article on this work has been published.[1]

*Syracuse University, Syracuse, New York.
†SOHIO Technical Center, Cleveland, Ohio and Case Western Reserve University, Cleveland, Ohio.
[1]T. Biswas, F. Rohrlich and M. King, Nuovo Cimento 77, 49 (1983).

j. Hamiltonian Lattice Gauge Theory (B. D. Day and F. Coester)

Quantum chromodynamics (QCD) is generally accepted as the fundamental basis for the theory of nucleons, mesons and their interactions. While Monte Carlo lattice gauge calculations have had some impressive success, a quantitative theory of nucleons and mesons based on QCD is still a distant goal. Given the inherent limitations of any one calculational approach it seems important to explore diverse avenues. The strong-coupling limit of Hamiltonian lattice gauge theories is a promising point of departure for the construction of nonperturbative approximations. Recently Mendes has applied the Coester-Haag scheme for the construction of field-theory vacuum states to lattice gauge theories. The Coester-Haag construction is closely related to the coupled cluster equations which form the basis for successful nonperturbative approximations to many-body states in nuclear physics and quantum chemistry. We are exploring the possibilities of obtaining systematic nonperturbative approximations to lattice gauge theories along these lines. Initial explorations have focussed on an Abelian model in two space dimensions.

k. Quark Model Hadron Interactions (F. Coester and W. N. Polyzou*)

Quark models have been generally successful in describing single hadron spectroscopy. The essence of the confinement problem is that the quark dynamics must confine quarks to color-singlet hadrons while allowing hadrons to separate freely. The heuristic background for our models is lattice gauge theory in the Hamiltonian form of Kogut and Susskind. Following Greenberg and Hietarinta we use a string degree of freedom to partition quarks and antiquarks into singlets. In zero order this scheme produces quarks confined to noninteracting hadrons in a manifestly Poincaré invariant manner. The interactions between hadrons are produced by string-breaking and string-rearrangement mechanisms. A paper on this work was contributed to the "10th International Conference on Few-Body Problems in Physics" at Karlsruhe, 1983.

*University of Iowa, Iowa City, Iowa.

ℓ. Static Bag Source Meson Field Theory (John A. Parmentola)

An important factor in the role quarks will ultimately play in nuclear physics is the size of the quark core of the nucleon. Is its radius about equal to the charge radius of the proton or is it much smaller? Chiral bags provide useful models for the study of the consequences of various assumptions. The effective coupling to the meson field is stronger for smaller bags. For "little bags" perturbative treatment of the meson field or the truncation of the Fock space to one or two mesons do not yield legitimate approximations and some modes of the meson field become collective degrees of freedom of the physical nucleon. In general these collective degrees of freedom cannot be treated classically. For exploratory purposes we have investigated in quantitative detail a static source meson field theory in which only the nucleon isospin degrees of freedom are coupled linearly to a scalar-isovector meson field. We find that there exist reasonable values of the coupling constant g (~4) and the source radius R (~0.3 fm) for which the strong coupling approximation is valid. The lowest lying collective excitation of the dressed nucleon is a rotational isospin mode with isospin $\frac{3}{2}$. If we allow an intrinsic isobar excitation of the source (bare Δ) the strong coupling approximation is valid for significantly smaller values of the coupling constant or larger bag radii. In that case we find a bare Δ component in the dressed nucleon of 36%. Meson nucleon scattering in this model has been investigated numerically. A paper on published. These results are encouraging. They justify the more elaborate calculations required to treat the coupling of the pion field to a little chiral bag with intrinsic excitations.

m. Implications of a Small Bag Radius (John A. Parmentola)

We consider the possibility that the bag radius of the nucleon is of the order of the proton Compton wavelength. The cloudy-bag Hamiltonian couples the spin and isospin, as well as the intrinsic isobar excitations of the bag, to the pion field. In the strong coupling approximation required for small bag radii some modes of the pion field become collective degrees of freedom of the physical nucleon. The nucleon so dressed is not unlike a triaxial molecule with rotational and three vibrational degrees of freedom. We have found approximate analytic wave functions for low lying baryon states. For a bag radius of .32 fm we find an average number of 6 pions in the dressed nucleon. Overall the consequences of this exploratory model agree with experimental values within about 30%; however the charge radius of the proton is too small. A paper on this work has been submitted for publication.

n. Consistency of Electromagnetic Current Operators and Relativistic Wave Functions (F. Coester and M. J. King)

Intense electron and photon beams provide much of the precision data on the structure of nuclei and the properties of nuclear matter. Probing short range structure requires large momentum transfer which inevitably involves relativistic effects. The directly observed quantities are the matrix elements of the electric charge and current densities. Inference from the data about the structure of the nuclear target requires a mutually consistent representation of the current operators and the wave functions representing the states of the target. The representations of the Lorentz transformations depend on the forces governing the target structure. It follows that current operators satisfying the covariance relations of free particles are not covariant in the presence of interactions. By combining results from quantum field theory and constraint dynamics we have found a systematic construction of the two-body current operators required by Lorentz covariance. The construction does not depend on an expansion in powers of the particle velocities. A preliminary report on this work was presented at the Sixth Pan American Workshop on Condensed Matter Theory at St. Louis, Sept. 20-Oct. 1, 1982. A paper is being prepared for publication.

o. Electromagnetic Form Factors of the Deuteron for Arbitrary Momentum Transfer (F. Coester, W. Polyzou,* T.-S. H. Lee, and K. Ohta†

For a meaningful calculation of electromagnetic form factors of the deuteron, it is essential that the current-density operators and the deuteron wave functions transform under Lorentz boosts in a mutually consistent manner. This consistency can be achieved without the introduction of interaction currents by imposing a light front symmetry on conventional deuteron wave functions. The advantage of this representation is that single-nucleon and meson exchange contributions to the form factors each satisfy the Lorentz consistency separately. Work on a numerical implementation of this scheme is in progress.

---

*University of Iowa, Iowa City, Iowa.
†University of Tokyo, Tokyo, Japan.

B. VARIATIONAL CALCULATION OF FINITE MANY-BODY SYSTEMS

(S. C. Pieper, R. B. Wiringa, A. R. Bodmer, and collaborators from other institutions)

The methods of calculating finite many-body systems initiated in 1983 have been pursued, leading to a number of interesting results in 1984. The work on ^{4}He droplets was completed, and first calculations of the more difficult ^{3}He Fermion droplets were done. A second topic concerned hypernuclei where the variation in binding energy in going from s-shell hypernuclei through some intermediate cases to binding of a Λ in nuclear matter was studied to find the dependence on the ΛN and ΛNN forces. Specific results are given in the following.

a. Bound States of Quantal Many-Body Systems (S. C. Pieper, R. B. Wiringa, V. R. Pandharipande,* J. G. Zabolitzky,† and U. Helmbrecht≠)

In the past 30 years, there has been much progress in the computation of the ground-state properties of infinite quantum liquids such as nuclear matter or liquid ^{4}He or ^{3}He. For given interactions, accurate calculations of the ground states of three- or four-particle systems have also been made. However there has been relatively little work on quantum-mechanical calculations of large (more than four particles), but finite, systems of particles interacting with given potentials. We have been developing Monte Carlo techniques for the computation of bound-state properties of such systems. Our goal is to eventually apply these techniques to nuclei with reasonably realistic potentials. At Argonne and Urbana we are performing variational calculations which give an upper bound for the ground-state energy while Green's function Monte Carlo (GFMC) calculations are being used at Bochum and Cologne. The latter method gives (up to statistical errors) the exact ground-state energy and density distribution but requires much lengthier calculations; these calculations are not possible on the computers available at Argonne.

We have completed a study of the ground states of droplets of ^{4}He, and are now studying the first 0^+ excited states of such droplets. This is a simple system since we do not have to consider the complications of spin degrees of freedom and antisymmetrization. Also the He-He potential is a function of just the inter-atomic distance and the three-body potential is weak enough to be ignored.

---
*University of Illinois, Urbana, Illinois.
†University of Cologne, Cologne, Germany.
≠Ruhr University, Bochum, Germany.

We are also now working on the Fermi ^{3}He system in which spin and antisymmetrization must be taken into account. Fermi systems are much more difficult than Bose system for the GFMC method and it appears to us that only the VMC method being developed at Argonne will be practical for these studies.

Although the liquid He droplet computations may be considered as warm-up exercises for the calculation of nuclei, this work is interesting in itself. The binding energies and radius parameters of the droplets may be expanded as power series in $N^{-1/3}$, where N is the number of atoms in a droplet. The resulting series appear to be qualitatively different from the results of the hydrodynamical approximations currently being used in neutron-star calculations. The extrapolation of such series to $N=\infty$ may be compared with the infinite liquid calculations to learn something about the reliability of the extrapolations used to find the "experimental" properties of nuclear matter. It also appears that these series may give the best available values for the surface energy and surface profile of infinite liquids for a given potential; there have been very few direct calculations of these.

b. Variational Monte Carlo Calculations of ^{4}He Droplets
(S. C. Pieper, R. B. Wiringa and V. R. Pandharipande*)

A program for variational Monte-Carlo calculations of droplets of 4He was completed in the previous year. In these calculations a variational wave function containing one-, two-, and three-particle correlations is used. The ground state energy is then a 3N-dimensional integral, where N is the number of atoms in the droplet. The integral is done by the Metropolis method. Because this is a variational calculation, the parameters of the correlation functions must be varied until the minimum ground state energy is found; this energy is then an upper bound on the correct energy.

In 1984 we completed our study of the ground states of ^{4}He droplets with a calculation for the 728-atom droplet. Liquid-drop expansions were used to analyze the properties of the droplets and to make extrapolations to the case of semi-infinite liquid ^{4}He. Our predictions of the volume and surface energies are in good agreement with experiment. The surface profile of the semi-infinite liquid cannot be directly measured; our results for this quantity disagree with a recent analysis (that we believe to be unreliable) of scattering of ^{4}He atoms from a ^{4}He surface. Results of this work have been published in Phys. Rev. Lett. 50, 1676 (1983).

*University of Illinois, Urbana, Illinois.

c. Variational Monte-Carlo Calculations of ^{3}He Droplets (S. C. Pieper, R. B. Wiringa and V. R. Pandharipande*)

During 1983 we have modified our boson VMC program for the case of Fermions of arbitrary degeneracy interacting via central potentials. A Slater determinant of single-particle wave functions is used for the Fermi statistics. Since only one column of the matrix changes for each atom moved, we can rapidly compute the change of the wave function as atoms are moved during the Monte Carlo random walk. This program has been applied to droplets of up to 112 ^{3}He atoms. The results so far do not seem satisfactory in that the central density of the large droplets has saturated at a value of about $\frac{2}{3}$ that of the infinite liquid.

*University of Illinois, Urbana, Illinois.

d. Binding Energies of Hypernuclei and 3-body ΛNN Forces (A. R. Bodmer, Q. N. Usmani* and J. Carlson†)

We have calculated the Λ separation energies of $^3_\Lambda$H, $^5_\Lambda$He, $^9_\Lambda$Be, $^{13}_\Lambda$C and of a Λ in nuclear matter (the well depth D_Λ), i.e. for A = 3, 5, 9, 13 and ∞, using an effective interaction method (EI). We compared our results to some published more accurate but more complex variational calculations for the A = 5 system and D_Λ. The EI and variational results for A = 5 and D_Λ agree to within a few %, and in particular for D_Λ indicate that the first order cluster result (equivalent to our EI result) is a very good approximation. Both central ΛN and ΛNN forces with a two-pion range were used. We found that the spin average ΛN interaction $\bar{V}$ (= $\frac{1}{4}$ singlet + $\frac{3}{4}$ triplet) is rather well determined by the scattering data, more or less independent of the spin dependence of the interaction. With this value of $\bar{V}$, $^5_\Lambda$He is very much overbound - an old result, sharpened by our analysis of the scattering data. With Wigner type ΛNN forces (no spin, isospin dependence), $B_\Lambda(^5_\Lambda\text{He})$ then determines the strength of these which turn out to be quite strongly repulsive. The ΛN and ΛNN forces so determined are then found to give good agreement between the calculated and experimental energies of $^9_\Lambda$Be, $^{13}_\Lambda$C and D_Λ when also a reasonable p-state ΛN interaction (≈ $\frac{1}{2}$ the strength of the s-state one) is used, consistent with the scattering data. In particular for

*Physics Dept., Aligarh Muslim University, Aligarh, India.
†Courant Institute, New York University, New York, New York.

${}^{9}_{\Lambda}Be$, which we treat with an $2\alpha+\Lambda$ model (see also III.A.f.) the ΛNN forces give rise to a uniquely determined 3-body repulsive $2\alpha\Lambda$ potential which is needed for agreement with the experimental value. Wigner type ΛNN forces may plausibly be considered as due to a modification of the ΛN force due to many-body effects, in particular modification of the propagators of the intermediate state nucleon or Σ in a coupled ΛN-ΣN channel approach. In fact the strength of the ΛNN forces we obtain is consistent with results obtained with earlier ΛN-ΣN coupled channel G-matrix calculations of D_Λ.

If the suppression of the ΛN interaction (which leads to repulsive ΛNN forces) occurs mainly for ${}^{3}S_{1}$ ΛN pairs, as is plausible if the ΛN-ΣN coupling is dominated by the one-pion exchange tensor potential, then one obtains a spin-dependent 3-body ΛNN force. This is equivalent to the spin independent ΛNN force previously used for spin-zero core nuclei but for $A = 4$ hypernuclei could give perhaps as much as 40% of the 0^{+}-1^{+} excitation energy. Results of this work have been accepted for publication.

e. Coulomb Interaction Effects for the A = 4 Hypernuclei (A. R. Bodmer and Q. N. Usmani*)

The difference $\Delta B_\Lambda = B_\Lambda({}^{4}_{\Lambda}He) - B_\Lambda({}^{4}_{\Lambda}H)$ to be attributed to CSB effects must include the contribution ΔB_c due to the Coulomb interaction. This increases $B_\Lambda({}^{4}_{\Lambda}H)$ relative to $B_\Lambda({}^{4}_{\Lambda}He)$ and hence $|\Delta B_c|$ must be added to the experimental difference. There is a long standing controversy about ΔB_c: Dalitz, Herndon and Tang (Nucl. Phys. B47 (1972) 109) on the basis of variational calculations obtain for (the ground state) $\Delta B_c \approx 0.2$ MeV, whereas Gibson and Lehmann (Nucl. Phys. A329 (1979) 308) using Faddeev calculations with separable interactions obtain only $\simeq 0.02$ MeV. We have made variational calculations (for both the ground and excited states) with the new feature of calculating ΔB_c as a function of the square of the charge $q^2 = se^2$ (with s varying from 0 to 9, the required value corresponding to $s = 1$). This tests the linearity with q^2, and hence the accuracy of the perturbation value, and also provides a more accurate value of ΔB_c by amplifying the effect of the Coulomb interaction. Within the accuracy of our calculations we obtain no

*Physics Dept., Aligarh Muslim University, Aligarh, India.

significant deviations from linearity with q^2. We obtain $\Delta B_c = 0.04 \pm .01$ MeV for the ground state, significantly smaller than the value of Dalitz et al., and $0.03 \pm .01$ for the excited state. In view of our small values of ΔB_c the values of ΔB_Λ to be attributed to CSB effects are therefore close to the experimental differences. This work is being completed and prepared for publication.

f. Alpha-Cluster Calculations of $^{9}_{\Lambda}Be$
(A. R. Bodmer, Q. N. Usmani* and J. Carlson†)

Variational calculations have been made for $^{9}_{\Lambda}Be$, $^{10}_{\Lambda\Lambda}Be$ and $^{6}_{\Lambda\Lambda}He$ using $2\alpha+\Lambda$, $2\alpha+2\Lambda$ and $\alpha+2\Lambda$ models respectively. The best available local $\alpha\alpha$ potentials (fitted to $\alpha\alpha$ phase shifts) are used. The $\alpha\Lambda$ potential is obtained by effective interaction calculations by folding effective ΛN and ΛNN potentials into the α-particle density to reproduce $B_\Lambda(^{5}_{\Lambda}He)$. As described in B.d., ΛNN Wigner forces also imply a repulsive $\alpha\alpha\Lambda$ potential.

In addition to the ground-state calculation for $^{9}_{\Lambda}Be$ described in B.d., we are also calculating the energy of the lowest excited (doublet) state built on the first $J = 2^+$ state of ^{8}Be. Preliminary calculations indicate an excitation energy of ≈ 3 MeV, implying that the state is particle stable (with respect to breakup into $^{5}_{\Lambda}He + \alpha$ at a threshold 3.5 MeV above the ground state) and that it should decay by γ transitions to the ground state.

*Physics Dept., Aligarh Muslim University, Aligarh, India.
†Courant Institute, New York University, New York, New York.

g. Binding Energies of $\Lambda\Lambda$ Hypernuclei and the $\Lambda\Lambda$ Interaction
(A. R. Bodmer, Q. N. Usmani* and J. Carlson†)

Of the two published $\Lambda\Lambda$ hypernuclear events, $^{6}_{\Lambda\Lambda}He$ and $^{10}_{\Lambda\Lambda}Be$, the latter is the best established with a small uncertainty in the quoted binding energy and hence is an almost unique source of information about the $\Lambda\Lambda$ interaction. We have therefore made variational calculations for $^{6}_{\Lambda\Lambda}He$ and $^{10}_{\Lambda\Lambda}Be$ with emphasis on the latter. In addition to the $\alpha\alpha$, $\alpha\Lambda$ and $\alpha\alpha\Lambda$ potentials already discussed, a wide range of phenomenological $\Lambda\Lambda$ potentials

*Physics Dept., Aligarh Muslim University, Aligarh, India.
†Courant Institute, New York University, New York, New York.

based on meson exchange models was considered. An approximately universal linear relation between the calculated values of $B_{\Lambda\Lambda}({}^{10}_{\Lambda\Lambda}Be)$ and of $B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He)$ is obtained. For the experimental value of $B_{\Lambda\Lambda}({}^{10}_{\Lambda\Lambda}Be) = 17.7 \pm 0.1$ MeV this relation predicts a value of $B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He)$ well below the lower limit of the quoted experimental value of 10.9 ± 0.6 MeV. For the experimental value of $B_{\Lambda\Lambda}({}^{10}_{\Lambda\Lambda}Be)$ we obtain large and negative values of the scattering length ($2.5 < -a < 3.5$ fm) for ΛΛ potentials with reasonable repulsive cores. Such values correspond to conditions not too far from a bound ${}^{1}S_{0}$ ΛΛ state and could indicate a 6-quark dibaryon state with the same quantum numbers and above the ΛΛ threshold. A paper on this work has been submitted for publication.

C. NUCLEAR SHELL THEORY AND NUCLEAR STRUCTURE

(D. Kurath, R. D. Lawson, and others)

Our interest lies in seeking manifestations of nuclear structure in interpretations of experiments. During 1984 several studies were completed, and effects of Δ admixture in nuclei were calculated for normally-forbidden M1 transitions and for a spectrum of M1 cases in the 1p-shell. A program was written to calculate (e,e') transitions given the shell-model one-body transition densities, and thus complement our existing (π,π') DWIA code in testing agreement with experiment.

a. High Spin States in ^{91}Tc (A. Amusa* and R. D. Lawson)

Recently the nucleus ^{91}Tc has been produced in a heavy ion reaction and the gamma decay modes of its high spin states have been studied. In order to check the consistency of the tentative spin assignments we have carried out a shell model calculation for this nucleus. $^{88}_{38}Sr_{50}$ was assumed to be a doubly closed shell core and the five valence protons and two neutron holes in $^{91}_{43}Tc_{48}$ were assumed to occupy the $2p_{1/2}$ and $1g_{9/2}$ single particle states. The residual two-body interaction was taken from the work of Serduke, Gloeckner and Lawson. The spectrum was predicted and the gamma-ray lifetimes and branching ratios of the levels were calculated. The shell-model results confirm the proposed experimental angular momentum assignments. Results of this work have been accepted for publication.

*University of Ife, Ile-Ife, Nigeria.

b. Quenching of Stretched Magnetic Transitions (A. Amusa* and R. D. Lawson)

Inelastic pion, electron and proton scattering to the yrast 6^- T=1 state in ^{28}Si all indicate that the transition strength is only 30% of that predicted by the $d^{12}_{5/2}+[d^{11}_{5/2} \times f_{7/2}]_{6^-}$ model. The pion and proton data also indicate that the population of the yrast 6^- T=0 state is only 15% of the $d^{12}_{5/2} + [d^{11}_{5/2} \times f_{7/2}]_{6^-}$ prediction. We have carried out calculations using the entire $(d_{5/2},s_{1/2})$ model space for the 0^+ ground state, and for the 6^- states the same $(d_{5/2},s_{1/2})$ model space was used with at most one nucleon allowed in $f_{7/2}$. With a $(d_{5/2},s_{1/2})$ interaction that fits the normal parity states near A=28 and use of the Schiffer-True potential for the ds-$f_{7/2}$ interaction, we predict the transition to the 6^- T=0 state to be quenched by a

*University of Ife, Ile-Ife, Nigeria.

factor of between 3 and 4 and that to the 6^- T=1 by about a factor of two. However, our model also predicts that the ratio of the spectroscopic factors for the $^{27}Al(^3He,d)^{28}Si$ reaction to the 6^- T=1 and T=0 states should also be 2:1, the same as predicted for inelastic scattering, whereas the experimental ratio is 1. Although this extension does not fit experiment, the model suggests that if the $d_{3/2}$ single particle level is included it may be possible to explain the data without introducing non-nucleonic degrees of freedom. A paper reporting this work has been published.

c. The Effect of the Δ Resonance on Magnetic Dipole Properties of Nuclei (R. D. Lawson)

It has been shown that for closed shell ± one nucleon nuclei the main effect of including the Δ can be taken into account by introducing an effective one-body operator of the form $\frac{1}{2}g_s\sigma_\mu\tau_3+g_p[\sigma\times Y_2]_{1\mu}\tau_3$. When the quark model phasing between the central and tensor transition potentials is used the contributions from g_s and g_p cancel for magnetic moments leading to only a small effect on these quantities. For M1 transitions the contributions come in with the same sign and quench the transition rates. The quenching of B(M1) increases with A ranging from 16.2% for the $d_{3/2}\to d_{5/2}$ transition in ^{17}O to 32.5% for the $p_{3/2}\to p_{1/2}$ decay in ^{208}Pb. Since the presence of the Δ gives rise to a$[\sigma\times Y_2]_{1\mu}$ effective operator it can contribute to ℓ-forbidden M1 transitions. For ^{39}K this gives $B(M1) = 4.1\times10^{-3}\mu_N^2$ for the $s^{-1}_{1/2}\to d^{-1}_{3/2}$ transition which is about a factor of four smaller than the experimental value. When there are several nucleons outside a closed shell there is also a two-body contribution. This can lead to M1 transitions between states of the identical nucleon configuration j^n. However, in contrast to the one-body term, where all nucleon pairs give a contribution, only the valence nucleons contribute to this transition rate and consequently the predicted B(M1) is small. For example in ^{51}V B(M1) for the transition $(\pi f_{7/2})^3_{5/2}\to(\pi f_{7/2})^3_{7/2}$ is predicted to be $6.7\times10^{-7}\mu_N^2$.

d. Analysis of Inelastic Scattering of Pions (T.-S. H. Lee and D. Kurath)

Our purpose is to exploit the isospin dependence of inelastic scattering of pions at energies near the (3,3) resonance in order to test the calculated transition densities to particular excited states which are obtained from shell model calculations. In many cases there is now data from inelastic electron scattering to these same states which provides added information about the transition densities. Therefore a plane-wave Born-approximation (e,e') code has been written which for light nuclei will provide form factors from the shell model transition density inputs for comparison with experiment.

One case where $\pi^{\pm}$ and electron scattering data exists is for stretched M4 transitions in ^{14}C presumed to arise from $p_{3/2}$ to $d_{5/2}$ transitions. However the probable presence of $d_{5/2}$ nucleons in the ground state can reduce the transition strength, and a sum-rule has been derived which shows that a 5% admixture can lead to a 10% reduction in strength. Analysis of the experimental results is being carried out in collaboration with several people from other institutions and a paper is in preparation.

We expect that a number of other cases will be available for comparison in the coming year.

e. Cluster Transfer in the $^{14}C(p,\alpha)^{11}B$ Reaction (D. Kurath)

A recent experiment at the University of Manitoba has measured pickup from ^{14}C to a number of states in ^{11}B. Comparison of relative cross-sections with a published calculation of Millener and Kurath shows qualitative agreement for the strong transitions. These early calculations did not allow for the presence of (2sd) nucleons in the ^{14}C ground state, so the effect of such admixture has been calculated. The result is improved agreement with observation for the fairly strong ground state transition, but worse agreement for the weak transitions to the lowest $1/2^-$ and second $3/2^-$ states. The weak cases may be due to other than cluster transfer.

f. Effect of Δ(1236) on M1 Properties of 1p-Shell Nuclei (D. Kurath and R. D. Lawson)

The effect of Δ-admixture in nuclear wave functions has been calculated for nuclei from A=11 to A=15. For M1 transitions, the contributions of the central and tensor parts of the NN-NΔ potential have the same sign and lead to a general decrease of the matrix elements of about 6%. In comparison to experiment this is in the direction to improve the degree of agreement although there are two transitions in ^{11}B and one in ^{12}C where the shell model calculation already gives too small a matrix element before the Δ is included. For magnetic moments of the yrast $3/2^-$ states, the contributions of the central and tensor parts tend to cancel so that the Δ has only a small effect on these moments and tends to make the agreement with experiment slightly worse. For the yrast $1/2^-$ magnetic moments there is also cancellation from the two contributions with the net effect of moving the moments outside the Schmidt lines. For the single-hole nucleus ^{15}N this effect of the Δ is needed to agree with experiment since it is known that the effect of meson exchange currents and core polarization decrease the calculated magnitude. However for ^{13}C these effects all seem to move the calculated value further from the measured value. Thus the overall evidence from 1p-shell M1 properties contains a number of difficulties for resolving the question of Δ admixture.

Table III-1 Comparison of experimental and theoretical values of M1 matrix elements. In column 4 the experimental values, in nuclear magnetons, are listed — for transitions the magnitude of the reduced matrix element and for diagonal cases the magnetic moment. In column 5 the ratio of the experimental value to the shell model prediction, calculated using the (8-16)POT matrix elements, are given. In column 6 the same ratio is tabulated when the effect of the Δ is included. Our designation "a" and "b" refer to the yrast and second states of given spin and isospin respectively.

Nucleus	$(JT\alpha)_f$	$(JT\alpha)_i$	Exp.[a]	Expt/s.m.	Expt/(s.m.+Δ)
			TRANSITIONS		
^{15}N	3/2 1/2 a	1/2 1/2 a	2.03±0.10	0.77	0.83
^{14}N	0 1 a	1 0 a	0.46±0.03	1.13	0.55
	2 1 a	1 0 a	2.5±0.2[b]	0.72	0.78
	0 1 a	1 0 b	4.4±0.3	0.66	0.71
^{14}C	1 1 a	0 1 a	1.30±0.15	0.68	0.73
^{13}C	1/2 1/2 b	1/2 1/2 a	1.3±0.1[c]	0.69	0.74
	3/2 1/2 a	1/2 1/2 a	1.7±0.1	0.75	0.82
	3/2 3/2 a	1/2 1/2 a	1.53±0.05	0.92	0.98
^{12}C	1 1 a	0 0 a	1.97±0.03	1.10	1.17
^{11}B	1/2 1/2 a	3/2 1/2 a	2.16±0.07	0.75	0.78
	3/2 1/2 b	3/2 1/2 a	2.19±0.05	0.93	0.98
	5/2 1/2 a	3/2 1/2 a	1.50±0.04	1.01	1.04
	1/2 1/2 a	3/2 1/2 b	2.89±0.10	1.09	1.14
			MAGNETIC MOMENTS		
^{15}N	1/2 1/2 a		−0.283	1.07	0.78
^{13}C	1/2 1/2 a		+0.702	0.93	0.83
^{13}B	3/2 3/2 a		+3.178	1.01	1.02
^{12}B	1 1 a		+1.003	1.32	1.28
^{11}B	3/2 1/2 a		+1.689	1.02	1.03

[a]Extracted from the compilations of F. Ajzenberg-Selove, Nucl. Phys. A336, 1 (1980); A360, 1 (1981).

[b]This value comes from the sum of B(M1) values of the 9.17 MeV and 10.43 MeV states which share the 1p transition strength from the ground state.

[c]From (e,e'); the value extracted from (γ,n_0) is 1.7±0.1.

D. INTERMEDIATE ENERGY PHYSICS

(T.-S. H. Lee, W. E. Kleppinger and others)

In recent years, one of the major developments in nuclear physics is to extend the conventional nuclear many-body theory to include nonnucleonic degrees of freedom, notably the π and Δ isobar. Such an extension is obviously needed to describe intermediate energy nuclear reactions which are characterized by excitation of baryon resonances and meson production. Our investigation in this direction consists of three parts. The first part is to investigate the dynamics of πN, NN and πNN systems. In 1984, we have successfully developed a meson theory of NN scattering up to 2 GeV. The outcome of this study is a meson-exchange many-body Hamiltonian for π, N, Δ, and $N^*(1470)$ isobars which is the basis of developing a unified theoretical description of nuclear dynamics at both the low and intermediate energies. The second part of our study is to apply the resultant many-body Hamiltonian to obtain a microscopic understanding of nuclear reactions induced by intermediate energy pions, and to see how nuclear structure can be studied with these reactions. The focus of this study in 1984 was the mechanism of pion absorption by finite nuclei. Quantitative descriptions of extensive data for (π,N) and (π,NN) reactions on light nuclei have been obtained. Our study provides an internally consistent theoretical understanding of the phenomenological isobar-hole model of pion-nucleus interactions. Based on the numerical results of our microscopic calculation of pion absorption and the isobar-hole model, we then developed appropriate approximations to incorporate nonstatic dynamical features arising from the Δ-nucleus interaction into the distorted-wave-impulse-approximation (DWIA) study of pion nucleus inelastic scattering.

The third part of our study aims to extend the many-body nuclear theory to include electromagnetic and weak interactions at intermediate energies. In 1984, we continued our study of Δ-electroproduction by incorporating the newly constructed meson-exchange Hamiltonian into the calculation of electron scattering from deuterons. We have also started to develop a systematic microscopic approach to study nuclear structure from (e,e'X) reactions which can be investigated in detail by using the future few-GeV electron accelerator.

a. Meson-exchange Hamiltonian for N, π, Δ and N^*(1470 MeV) Isobars (T.-S. H. Lee)

The starting point of our study of intermediate energy nuclear reactions is the construction of a many-body Hamiltonian for N, π and isobars. In our earlier development of the theory (1982 and 1983), we only considered the coupling between the πNN state and the isospin T=1 $NN \oplus N\Delta$ channels, and used separable forms to parameterize interactions. In 1984, we have employed the meson theory of nuclear force to improve the dynamical content of the theory, and also include the N^*(1470) isobar in order to describe NN scattering in the T=0 channel. The meson-exchange model consists of: (a) vertex interactions πN-Δ or N^*, and $\pi\Delta$-Δ or N^* with which an isobar model is constructed to describe the P_{33} and P_{11} πN scattering phase-shifts up to 1 GeV, (b) the transition interactions from NN to $N\Delta$, $\Delta\Delta$, NN^* and N^*N^* are determined from one-pion and one-rho exchange mechanisms, (c) the NN→NN interaction is directly derived from the Paris potential by using a momentum-dependent procedure to subtract the contributions from intermediate states involving Δ or N^*. The NN→NN scattering equation is cast into the familiar coupled-channel form, but with a highly nonlocal isobar self-energy $\Sigma(E,p)$ calculated from the vertex interactions $\pi N \leftrightarrow \Delta$ or N^* in a dynamical three-body approach. Good fits to all of the NN scattering phase-shifts of Arndt et al. up to 1 GeV are obtained. The model can be used for a unified approach to study the isobar-nucleus dynamics at both low and intermediate energies. Results have been published.[1,2]

The model also describes very well both the magnitudes and signs of the NN total cross sections σ^{tot}, $\Delta\sigma_T^{tot}$ and $\Delta\sigma_L^{tot}$ up to 2 GeV, except the strong energy dependences in the region near 800 MeV (Fig III-3). In 1985, we will investigate the origin of this problem in connection with necessary improvements of the model and the questions about the dibaryon resonances. The short range quark-gluon dynamics as described by the phenomenological QCD-based model will be incorporated in our study.

[1]Phys. Rev. Lett. 50, 1571 (1983).
[2]Phys. Rev. C 29, 195 (1984).

b. Microscopic Study of Pion Absorption by Finite Nuclei (T.-S. H. Lee, K. Ohta* and M. Thies†)

The excitation of a Δ resonance by a $\pi N \leftrightarrow \Delta$ interaction is the dominant mechanism of the pion nucleus interaction. A microscopic description of the annihilation of the Δ in the nuclear medium is required to complete the mechanism of pion absorption in a many-body description of pion nucleus reactions and to understand the successful phenomenological isobar-hole model. Applying the many-body Hamiltonian for π, N and Δ described in D.a., we have carried out extensive calculations of pion absorption by light nuclei with the assumption that the absorption mechanism is a two-body Δ excitation

*University of Tokyo, Tokyo, Japan.
†Free University, Amsterdam, The Netherlands.

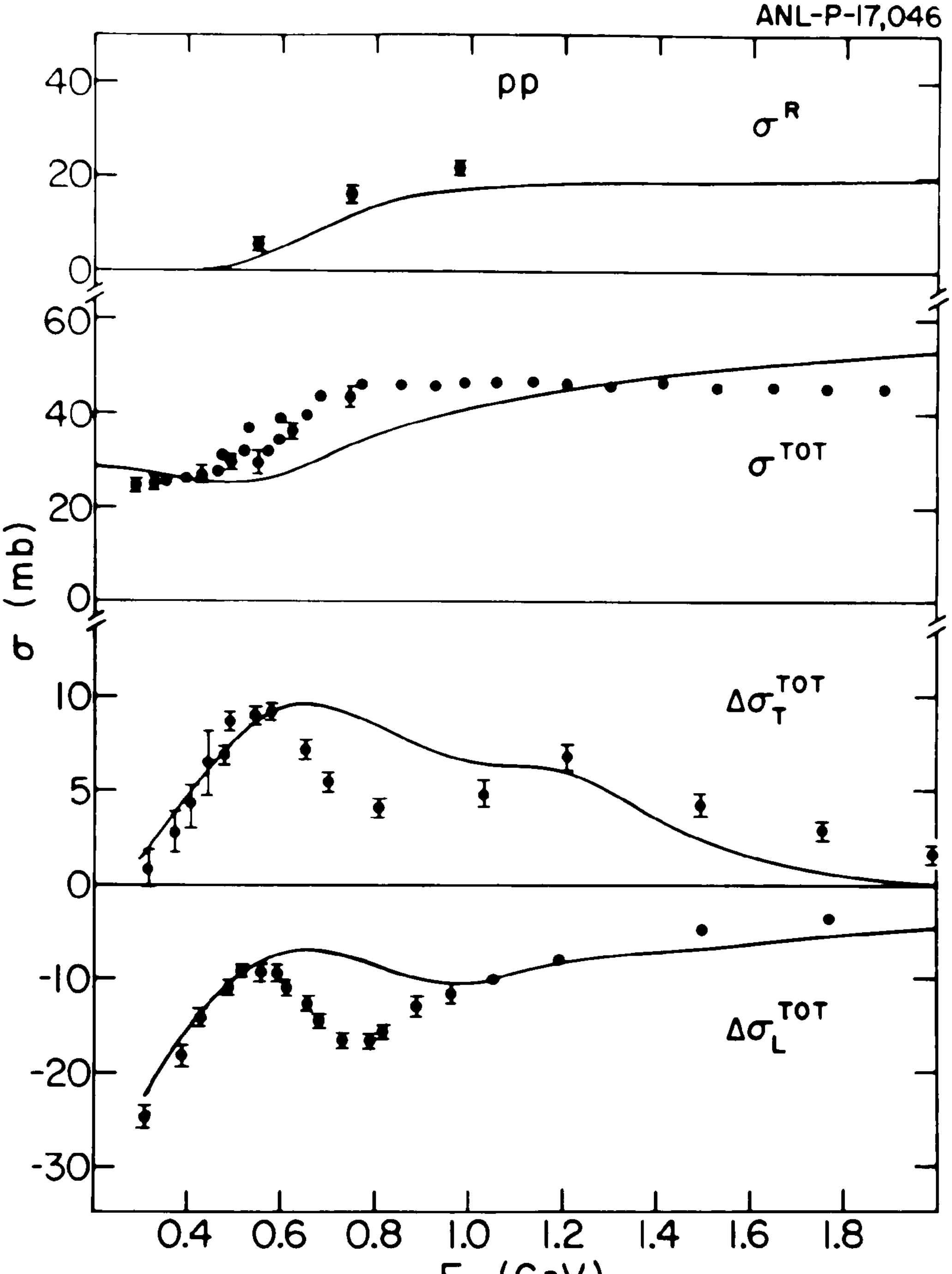

Figure III-3. The calculated pp reaction cross section σ^R, total cross sections σ^{tot}, $\Delta\sigma_T^{tot} = (\sigma^{tot}(\uparrow\uparrow) - \sigma^{tot}(\uparrow\downarrow))$, $\Delta\sigma_L^{tot} = (\sigma^{tot}(\rightleftarrows) - \sigma^{tot}(\rightrightarrows))$ are compared with the data.

process $\pi NN \leftrightarrow N\Delta \leftrightarrow NN$. General quantitative agreements with the data of (π^+,p) and (π^+,pp) reactions on ^3He and ^4He have been obtained. The data of (π^+,p) from ^{12}C and ^{16}O can also be described to a very large extent by the same mechanism, when the isobar-hole model, which gives an accurate description of pion scattering, is used to describe the initial π-nucleus interaction (Figs. III-4 and III-5. Combining our present results of pion absorption and previous calculation of inclusive (π,π') scattering, we have established a microscopic foundation of the phenomenological isobar-hole model. A paper describing these results has been submitted for publication.

The calculations of (π^-,pn) and (π^-,p) with the same $\pi NN \leftrightarrow N\Delta \leftrightarrow NN$ mechanism are less successful. We explored the origin of the problem in a careful calculation of $^3He(\pi^-,pn)$ reaction, and found that only the p-wave $N\Delta$ intermediate state in the two-body $\pi NN \leftrightarrow N\Delta \leftrightarrow NN$ absorption mechanism contributes to this process. This $N\Delta$ p-wave contribution is much weaker than the $N\Delta$ s-wave which dominates the absorption of π^+ by deuteron and He. Also, it decreases very quickly to be negligibly small as pion energy is changed away from the resonance energy, yielding a very large ratio $(\pi^+,pp)/(\pi^-,pn)$ at 65 MeV in contradiction to the data. Other nonresonant two-body absorption mechanisms leading to a final T=0 NN channel must be included. We have investigated the absorption mechanism through the nucleon pole $\pi NN \leftrightarrow NN \leftrightarrow NN$, where the final NN state is in T=0 channel. By using the standard Chew-Low vertex for $\pi N \leftrightarrow N$ and calculating the T=0 $NN \leftrightarrow NN$ transition matrix from the conventional low energy NN potential, we can describe the general features of the $^3He(\pi^-,pn)$ reaction. The calculated ratios $\sigma(\pi^+,pp)/\sigma(\pi^-,pn)$ show strong energy- and angle-dependence, in agreement with several preliminary data. A paper describing our findings is being prepared for publication. The model will be examined in more detail by comparing our calculation with the extensive data of $^3He(\pi,NN)$ being analyzed by the experimental groups at Argonne, TRIUMF and SIN.

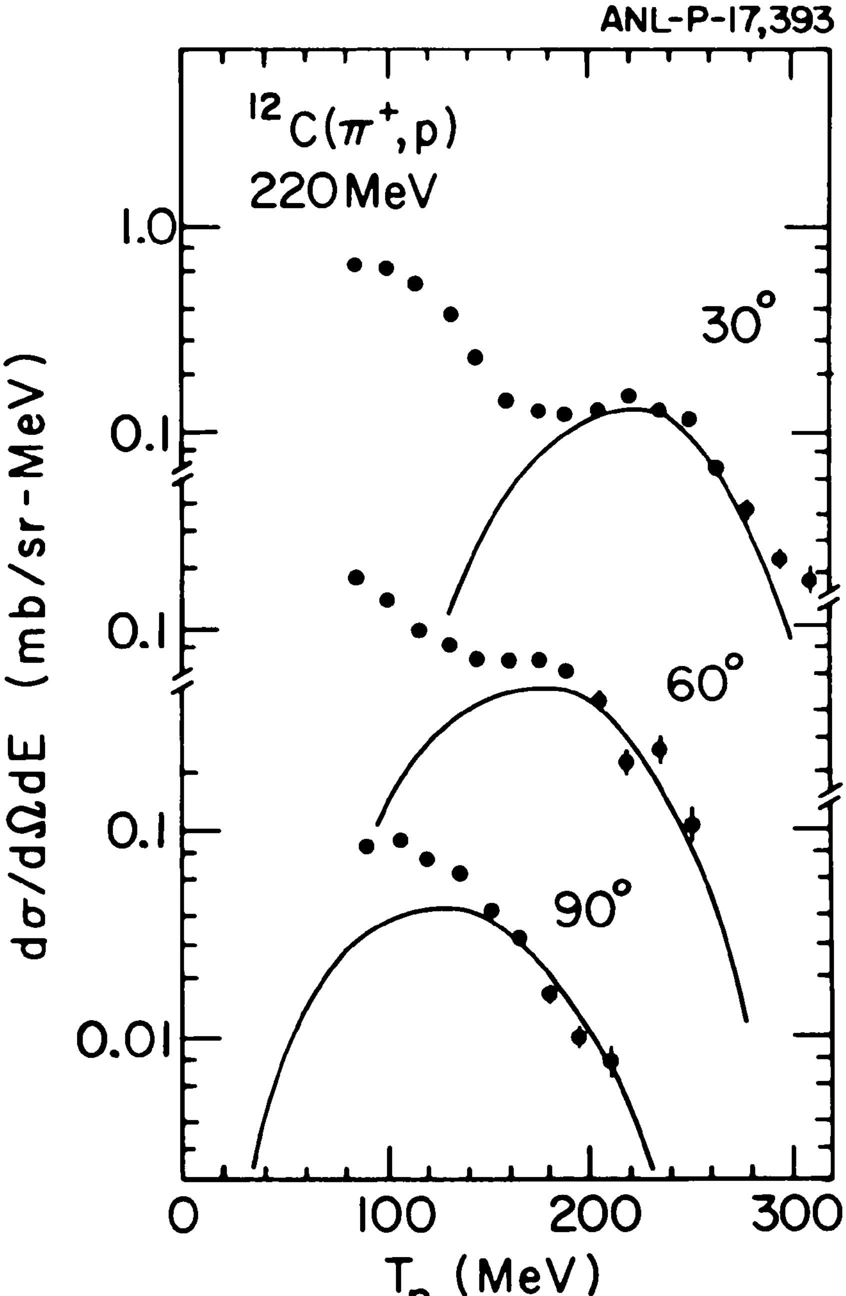

Figure III-4. Theoretical calculations (smooth curves) of $^{12}C(\pi^+,p)$ are compared with the data.

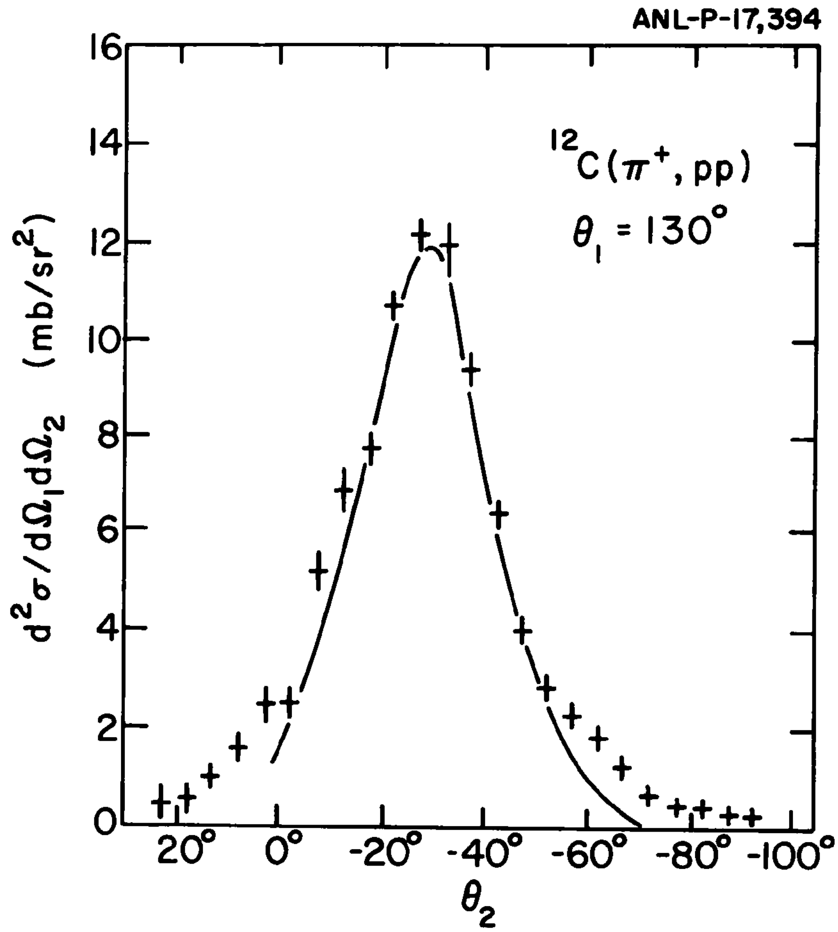

Figure III-5. Theoretical calculation (smooth curve) of the $^{13}C(\pi^+,pp)$ reaction is compared with the data.

c. Derivation of DWIA from the Δ-hole Model of Pion Scattering (T.-S. H. Lee and E. Moniz*)

A pion-nucleus optical potential has been successfully deduced, in the local density approximation, from the Δ-hole model of pion scattering. The essential result of this derivation is a medium-modified πN scattering matrix which contains many nonstatic effects owing to nucleon recoil, Pauli blocking, and pion absorption. We are extending this approach to improve our DWIA Code for the study of pion inelastic and charge-exchange scattering. The improved DWIA model will be used to study many existing data of (π,π') which are beyond the description of the current static DWIA model.

*Massachusetts Institute of Technology, Cambridge, Massachusetts.

d. Electroproduction of Δ's From Light Nuclei (T.-S. H. Lee and K. Ohta*)

Since the virtual γ interacts weakly with the nuclear medium, the Δ can be produced throughout the nuclear volume, whereas the pion produces Δ's mainly on the nuclear surface. Furthermore if the incident electron energy is several GeV, one can produce a very fast off-shell Δ with momentum of many GeV/c. The Δ produced in the π-nucleus interaction is mainly on-shell with momentum about 0.3 GeV/c. Therefore the (e,e') study can examine the dependence of Δ-nucleus dynamics on the nuclear density and on the Δ momentum.The two-body electromagnetic current owing to the Δ excitation can be straightforwardly calculated in our approach by adding a γN→Δ vertex interaction to the meson-exchange Hamiltonian described in D.a. The resulting mechanism γNN→NΔ→NN must dominate in (e,e') on nuclei when the energy transferred to the nucleus is about 300 MeV and involves excitation of a nucleon to the Δ state. As a first test we have calculated the electroproduction of Δ's from the deuteron by using our separable model Hamiltonian constructed in 1982. It is found that the calculated cross sections only reproduce d(e,e') qualitatively, indicating the deficiency of using the separable model to describe off-shell NΔ→NN transitions. We are now carrying out the calculation using the newly constructed meson-exchange model Hamiltonian. We expect to finish the study of d(e,e') in the summer of 1984, and will extend the approach to study heavy nuclei.

*University of Tokyo, Tokyo, Japan.

e. Study of Weak Neutral-Current Effects in (e,e'X) Reactions (W. E. Kleppinger)

In electron scattering from nuclei, in addition to the usual electromagnetic interaction, unified models of the electromagnetic and weak interactions predict an additional weak neutral-current interaction. When this additional interaction is included, a parity-violating contribution to the cross section, due to the interference of the electromagnetic and neutral-weak currents, is present. The purpose of this work was to examine how these effects can be explored in (e,e'X) reactions with polarized incident electrons, where in addition to detecting the scattered electron, a decay particle X, emitted by the excited target nucleus, is also detected. It is found that new interference terms appear in the cross section that are not present in inelastic (e,e') scattering. A model calculation that assumed that the target was excited to a single, intermediate resonance indicates that the angular distribution of X is sensitive to these new terms. Results of this work have been submitted for publication.

f. Study of (e,e'X) Reaction in the Nuclear Shell Model (W. E. Kleppinger)

The (e,e'X) reaction (where X can be nucleon or other hadrons) is one of the main research subjects which will be investigated in the near future using high-duty factor electron accelerators. We are developing a microscopic approach to the problem assuming that the nuclear states can be described by the nuclear shell model. In the one-photon-exchange approximation, the (e,e'X) amplitudes can then be expressed in terms of matrix elements of current operators between single particle wavefunctions, and the transition densities between nuclear states. At the present time we are investigating (e,e'N) reactions in the region where the one-body nucleonic current dominates the reaction mechanism. As a first step, the (e,e'p) and (e,e'n) cross sections have been calculated for ^{12}C and ^{40}Ca using harmonic oscillator wavefunctions and plane waves for the outgoing nucleons. These calculations are needed to check our computation program against previous work by deForest. Using these calculations, we have investigated qualitatively the energy- and momentum-dependences of various (e,e'N) amplitudes on the structure of the single particle wavefunction. The use of high energy GeV-electron scattering is found to be advantageous. We are now improving our calculations using realistic single particle wavefunctions for the bound nucleons and distorted waves for the outgoing nucleons, calculated with an appropriate optical potential.

In 1985, we plan to extend our approach to study two-body currents, and use sophisticated shell model wavefunctions in the study of 1p-shell nuclei. The production of hypernuclei by $(e,e'k^{+})$ will also be investigated.

E. HEAVY-ION INTERACTIONS

(S. C. Pieper and others)

The program, Ptolemy, has been used in coupled-channel calculations of inelastic scattering and also to calculate the cross section for fusion near the Coulomb barrier. Development of the program's capabilities is continuing. Specific examples are given below.

a. Analysis of Heavy-ion Fusion Near the Barrier (S. C. Pieper and S. Landowne*)

Fusion of heavy ions at energies just beneath the Coulomb barrier has recently generated much interest because the straightforward optical-model calculations of the total reaction cross section underestimate the fusion cross sections by several orders of magnitude. In simple model calculations, Landowne and others had shown the importance of coupled-channels effects in these predictions. We have used Ptolemy to make coupled-channels calculations for $^{12}C+^{12}C$ and $^{58}Ni+^{58}Ni$ at energies near the Coulomb barrier. In the case of ^{58}Ni, we included four 2^+ states, the first 3^- and 4^+ states, and the channel in which both ^{58}Ni are in the first 2^+ state. At the low energies considered, only the 2^+ state could be excited in ^{12}C. We found that, as expected, the cross sections in the Ni system are drastically increased by the coupled-channels, although the data are still underpredicted. However, in the C system, the coupled-channels calculation predicts a lower fusion cross section. This result was unexpected and is presumably due to the closeness of the excitation threshold to the Coulomb barrier. An article on the Ni calculations has been submitted for publication.

*Technical University, Munich, West Germany.

b. Analysis of $^{28}Si+^{28}Si$ Scattering (S. C. Pieper)

Within the last few years, extensive data on the elastic and inelastic scattering of ^{28}Si from ^{28}Si have been measured at Argonne and Brookhaven. Detailed angular distributions for resolved states up to the channel in which one ^{28}Si is in the first 2^+ state and the other in the first 4^+ state have been obtained at a number of energies. We have concentrated on attempting to fit the data at c.m. angles less than 60°; the back-angle data shows large resonance-like structures that can probably not be accounted for in coupled channels calculations with optical potentials. In coupled channels calculations using a deformed rotor model of ^{28}Si we find the inclusion of an intrinsic hexadecapole moment to be essential to reproducing the 4^+ cross sections. However we have not yet succeeded in reproducing the data for the mutual 2^+, 2^+ channel. Work on this problem is continuing.

c. Unitarity in Coupled-Channels Calculations (S. C. Pieper)

In coupled-channels calculations of inelastic scattering, the coupling potential is usually derived in some way from the complex optical potential. The method used might be projection with a spherical harmonic in the case of the deformed rotor model, or an expansion in derivatives for either the first-and second-order rotational models or the vibrational models. For single-channel scattering with complex potentials, the imaginary part of the potential must be everywhere negative to avoid the creation of flux and possible violation of unitarity. For coupled channels the corresponding requirement is that the imaginary potential be a negative-definite operator in the channel space. We have found that incomplete calculations (first-order expansion, failure to include reorientation, etc.) for the deformed rotor can violate this requirement. Complete calculations with the vibrational model can also violate this requirement. We intend to finish this work in 1984.

F. OTHER THEORETICAL PHYSICS

a. Aharonov-Bohm Effect as a Possible Probe of Unusual Surface States on Conductors (M. Peshkin)

The successful development of electron holography at the Hitachi Central Research Laboratory has revived interest in the possibility that the Aharonov-Bohm (AB) effect may under some circumstances be suppressed by an electrostatic shield around the magnetic field. The point is that electron holography has achieved the sensitivity necessary to detect even partial suppression of the AB effect, and may therefore serve as a unique probe of the thin surface layer in which electrostatic shielding takes place. It is easily shown that normal electrons, ones which do not possess off diagonal long range order (ODLRO), cannot suppress the AB effect. Whether electrons in a state having ODLRO can suppress the AB effect is not yet known. We hope to be able to clarify that question in the near future. If the answer is affirmative, that will imply that AB effect has the possiblity of detecting phase transitions of electrons near the surface of conductors, such as the one which may have been seen by Fairbank and collaborators on copper surfaces at low temperatures. Although AB effect would be limited to detecting condensation to states with ODLRO, it might be far more sensitive than any other technique when ODLRO is present. A paper which reviews the status of these speculations will be published by the Japanese Physical Society.

b. Experience with Vector Processors (S. C. Pieper)

The Argonne program for Monte Carlo calculations of helium droplets was converted to two vector processors: the Cray I at the Max Planck Institute, Munich and the Cyber 205 at the Ruhr University, Bochum, Germany.

The conversion to the Cray-I was achieved without difficulty (almost no changes beyond changing IBM double- to Cray single-precision were necessary). The resulting program was a little less than twice as fast as on the Argonne IBM 370/195. With a little rewriting, the speed increased to 3-4 times faster than the /195. It is not clear how to make the program substantially faster.

The conversion on the CDC Cyber 205 was not so easy. A number of compiler bugs were encountered and, in the two weeks available, it was possible to get only a subset of the Bose version of the program working.

With the minimal changes necessary to make the program work, the speed increase was less than a factor of two. Obtaining significant further increases required extensive rewriting of the program in a pseudo Fortran that is usable only on the Cyber 205. This was done for the most time consuming subroutine, and the speed of just that subroutine was measured. The result was from 3 to 7 times faster than the /195, depending on the vector length.

The conclusion from this study is that the Cyber 205 can deliver more speed than the Cray-I but achieving such speed required an unacceptable amount of recoding with the resulting program being usable only on the Cyber 205. For both machines the Monte Carlo program ran at only a fraction of the theoretical speed.

IV. THE SUPERCONDUCTING LINAC

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

INTRODUCTION

The superconducting linac project at Argonne consists of a broad range of activities including (1) the continuing refinement of the existing prototype linac, (2) construction of the larger ATLAS linac, and (3) the development of the technology required for a proposed positive-ion injector for ATLAS. All three parts of the program involve developmental activities that are of rather general interest.

The superconducting linac program is jointly supported by the Chemistry and the Physics Divisions.

A. PROTOTYPE HEAVY-ION SUPERCONDUCTING LINAC

This project, started in mid-1975 and now completed, has been 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 for the FN tandem accelerator. The principal objectives of the project have been to develop a new accelerator technology and to build the prototype for a heavy-ion 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. The last two resonators of the planned 24-resonator system were installed in 1982.

The booster linac is now complete in all respects. Its main features have been outlined in previous Annual Reviews. Some effort is still being devoted to perfecting various subsystems of the accelerator, as outlined in Sec. V, but our developmental effort is now being devoted mainly to the ATLAS project and to the recently proposed positive-ion injector.

By now, the booster has been used extensively (~15,000 hr) to provide beams for nuclear-physics research. This operational experience is summarized in Sec. V of this document.

The booster will continue to be used in its present form until early 1985, when it will be incorporated into the ATLAS facility.

---

*Chemistry Division, ANL.

B. THE ATLAS PROJECT

The Argonne Tandem-Linac Accelerator System (ATLAS) is a heavy-ion accelerator being formed by enlarging the booster linac and by adding a large new target area, as shown in Fig. IV-1. 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 project was authorized in the FY 1982 budget at a level of $7.7 million, of which $4.0 million was appropriated in FY 1982, and the remainder in FY 1983. The project started officially in January 1982 when the initial funds were released. By the end of this reporting period (March 1983), the project was about 80% completed.

The construction of the ATLAS building addition got off to a very fast start and, because of economic conditions in the building industry, this has resulted in a considerable savings in cost. The first phase of construction, consisting of foundations and poured-concrete walls, was started in May 1982 and completed in October. The remaining work started in December 1982, and by the end of the present reporting period the work is almost completed and we have started to make use of parts of the new building.

One of the main technical objectives of the ATLAS project is to add three linac sections that can effectively accelerate the relatively fast projectiles produced by the booster linac. This required the fabrication of 18 new resonators. The first 9 of these will be our proven $\beta = 0.105$ type in order to make it easy to match the beam from the booster into the new linac. The other 9 units will be of a new type that is optimum for ions with $\beta = 0.16$ and operates at an RF frequency of 145.5 MHz, 3/2 times the frequency of the booster units. The status of development of the new accelerating structure is summarized in section C.1.a. The fabrication of all of the resonators needed for ATLAS is expected to be completed by September 1984.

An impression of the status of the accelerator part of the ATLAS project is given by Fig. IV-2, which is a view from the present output-beam line into the tunnel where the ATLAS linac is being installed. The welder is working on the helium distribution system, and the large tank on the left is one of the three new cryostats being added by the ATLAS project.

It is expected that all major components of the ATLAS linac will be installed by late 1984, and testing of the RF and cryogenic systems will start in early 1985. The first test beams will be accelerated in April 1985.

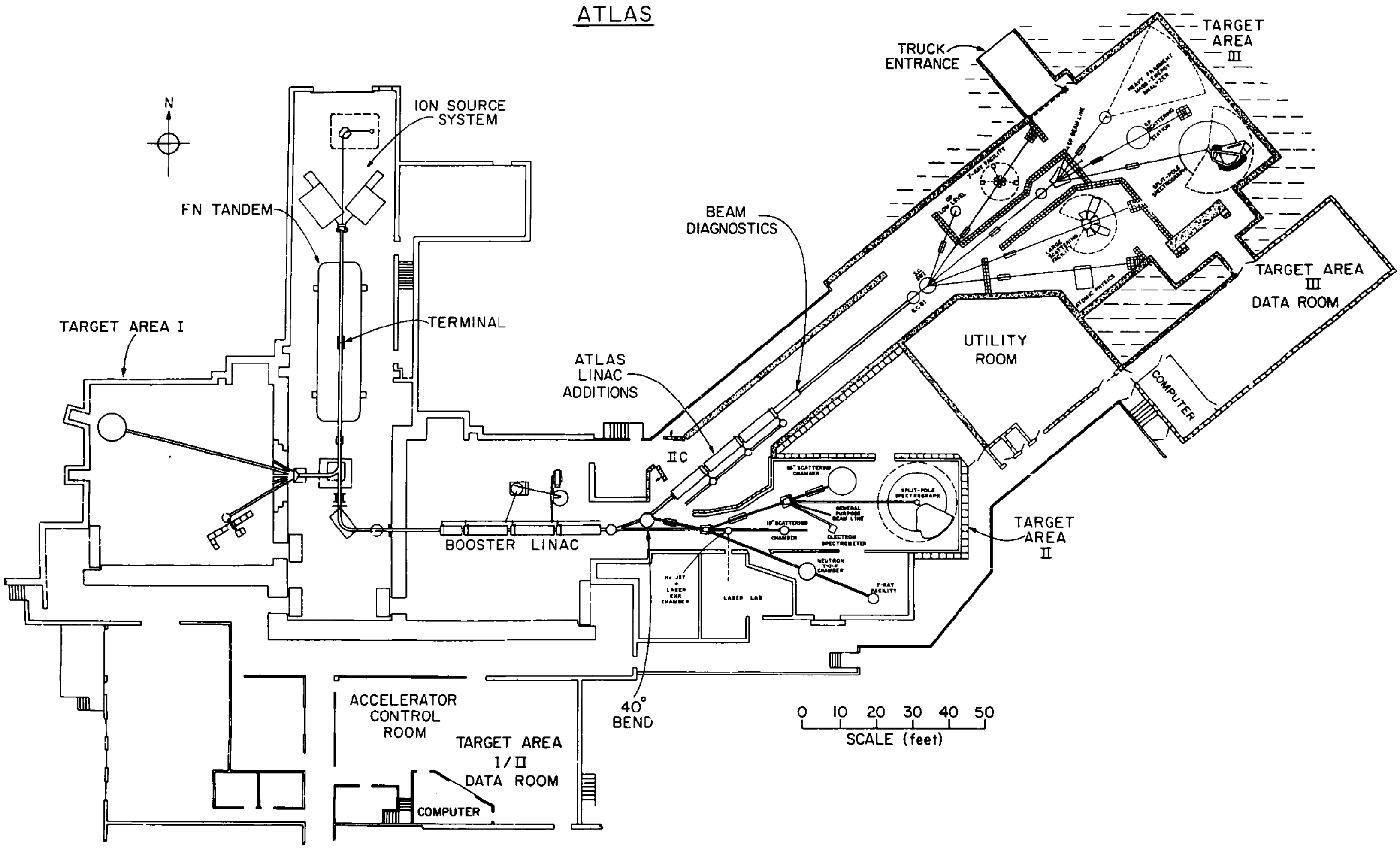

Figure IV-1. Layout of the ATLAS facility

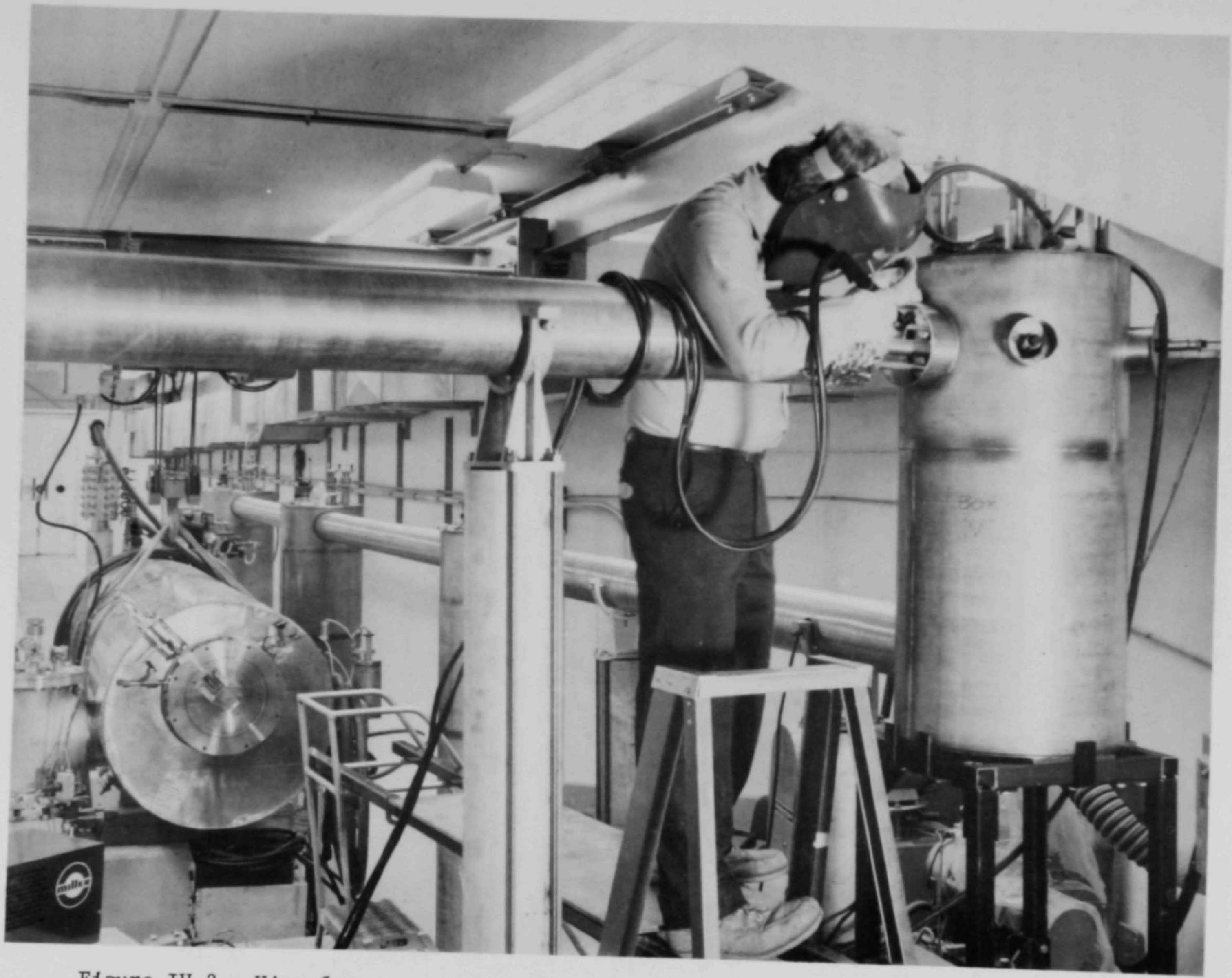

Figure IV-2. View from present output-beam line into tunnel where ATLAS linac is being installed.

C. INVESTIGATIONS OF SUPERCONDUCTING-LINAC TECHNOLOGY

1. Superconducting Accelerating Structures

K. W. Shepard, G. P. Zinkann, and P. Markovich*

a. Resonators for ATLAS

In last year's report, we discussed the design and fabrication of the prototype of a $\beta = 0.16$ resonator (designated type S) intended for use at the high-energy end of the ATLAS linac. The initial tests on the unit were encouraging but the accelerating field of 3.2 MV/m was lower than had been expected. During the past year the performance was improved somewhat, with the final performance being an accelerating field of 3.6 MV/m for a power dissipation of 4W. This performance was judged to be satisfactory but not as good as had been hoped for.

In view of the effort required to fabricate the S-type resonator, we decided to simplify the design of the $\beta = 0.16$ unit by making it similar to the well-established $\beta = 0.105$ unit, the only difference being that the loading arm was shortened enough to increase the RF frequency to $3/2 \times 97 = 145.5$ MHz. This simplified unit was initially labeled the S' type, later changed to V type. The prototype V-type resonator was completed about four months after the decision to build it. Somewhat to our surprise, the performance turned out to be excellent: the accelerating field is 3.9 MV/m for a power dissipation of 4W. This field level is indistinguishable from that obtained for the similar unit with $\beta = 0.105$ and tends to support the idea that electron loading is independent of the RF frequency.

b. Quarter-Wave Resonator

During the past year there has been widespread interest in the good performance of a quarter-wave superconducting resonator built at SUNY Stony Brook by Brennan and Ben Zvi. This unit has a lead superconductor and operates at an RF frequency of roughly 160 MHz. From our point of view the main interest of this quarter-wave unit is the demonstration that multipactoring is not necessarily an absolute barrier to operation, as had seemed to be the case for several earlier quarter-wave lines.

In an effort to determine whether niobium has any clear advantage or some unforseen disadvantage for the quarter-wave design, we have constructed a niobium unit with an RF frequency of 140 MHZ and $\beta \approx 0.14$. A resonator of this kind (if the frequency were 145.5 MHz) could be used in the high-energy end of the ATLAS linac, but such a use is not planned at this time.

The quarter-wave unit made of niobium has just been completed and testing is about to start. It is hoped that the unit will help to answer the following three questions: (1) is multipactoring an inherently serious problem for the quarter-wave design, (2) does electron loading at high fields depend on voltage drop or only on maximum surface electric field, as is often assumed, and (3) is the RF frequency markedly more stable for the quarter-wave unit than for our split-ring design?

The answers to these questions are important for the resonator investigations outlined in Section C.1.c. below.

c. Superconducting Accelerating Structures for Very Slow Ions

The superconducting accelerating structures used to date for heavy ions cover only a very limited range in synchronous velocity, namely, $0.04 < \beta < 0.11$. The new V-type structure described in Section I.A.a. above will soon extend this range upward to 0.16. We have now started an investigation aimed at extending the range to very much lower velocity, hopefully to $\beta \approx 0.008$.

The objective of this new investigation is to develop accelerating structures that are appropriate for a positive-ion injector linac that could replace the tandem in a tandem-linac accelerator system, a concept that is outlined in a following section. In this concept, the ions from the source are expected to have a velocity of only about $\beta = 0.008$ for the heaviest ions, which will require some important changes in the design of superconducting accelerating structures. In particular, the low velocity makes it highly desirable to have a much lower RF frequency than has been used heretofore in superconducting structures. We have tentatively concluded that the optimum frequency for us is 48.5 MHz, half of our standard frequency of 97 MHz. This is low enough to be consistent with the expected ion-bunch width and to permit the effective accelerating field to be large, and at the same time it is high enough to result in a structure of reasonable overall size.

At this early stage of the work, we are concentrating on the design of a 4-gap structure formed by three drift tubes and the resonator end plates. Two of the drift tubes would be driven by a quarter-wave line with a length chosen to resonate at 48.5 MHz. The fabrication of copper models will start soon, and work on niobium prototypes is expected to start in late 1984.

The major uncertainties about these very-low-β resonators are the usual ones: how serious are mechanical vibrations, multipactoring, and field-emission-like electron loading? It is expected that copper models will provide information about mechanical vibrations; the upcoming tests on our 140-MHz quarter-wave line will say something about multipactoring; and our experience with the $\beta = 0.06$ and $\beta = 0.105$ split-ring resonators suggests that electron loading is diminished when the width of the accelerating gap is reduced.

2. Time-of-Flight Technology

R. C. Pardo, K. W. Johnson,* and B. E. Clifft*

a. Energy-Measurement System

In previous reports we have described a continuous, nondestructive energy-measurement system that makes use of the phase difference (flight time) between two beam-excited resonators. This system is now used regularly to measure beam energies with an apparent accuracy of a few parts in 10^4, but there continue to be occasional questions about the reliability of the system. In every such incident, however, it has turned out that the apparent problem results from one of two causes: a) a minor programming bug in the energy-measurement system or b) an error in the reference energy provided by the tandem-beam analyzer magnet. This latter problem is caused by the complexity of the magnetic-rigidity spectrum of heavy ions after passing through two strippers; and consequently it is the time-of-flight system rather than the magnet that is giving the correct energy.

In summary, then, we are still confident that our time-of-flight system is a good solution to the energy-measurement problem for weak pulsed beams of heavy ions.

3. Superconducting Magnets

a. Bending Magnet (R. C. Pardo and J. M. Bogaty)

The superconducting dipole magnet being developed as a prototype for several possible applications has been completed and successfully tested. We have concluded that the optimum use is as a beam switch at the entrance to the new ATLAS experimental hall. The magnet will be installed at this location during 1984.

The operation of the superconducting magnet has proven to be quite satisfactory for its application. After three quenches, the maximum central field was 4.9 tesla, which implies a bending power of 2.4 T-m. Since the maximum bending angle that is required is 31°, the mass-energy product of the magnet is 848, which is high enough to handle all useful beams from ATLAS.

b. Solenoid Focusing Magnets (R. Benaroya)

Our superconducting linac makes use of superconducting solenoids to focus the beam periodically. These lens have proven to be very satisfactory in the present linac and consequently will also be used in the ATLAS addition. However, because of the higher energies involved, it is desirable to increase the focusing power of the new solenoids for ATLAS. This has been achieved by increasing the thickness of coil winding. The resulting units have the following parameters: overall length (including iron shield), 12 inches; diameter, 8 inches; maximum central field, 8.5 tesla at 4.6 K; focusing power 12.7 T^2m. Thus, it is a very strong compact lens. For example, the focal length would be only 52 cm for 20-MeV protons.

c. Heavy-Ion Beam Splitter (R. C. Pardo)

One objective of the ATLAS project is to form two independent beams for simultaneous use in different experiments. This is to be done at the junction between the existing booster linac and the new ATLAS section, where the beam can have components from several charge states that are formed in the pre-linac stripper. In the approach that we are now pursuing, two beams are formed by a two-step process: (1) the charge states in the beam out of the booster linac are dispersed by bending the beam with a magnet and then (2) two of these charge states are separated out by bending one charge state in a second magnetic field and allowing another charge state to enter a flux shield that forms a straight path through this field.

A superconducting flux shield that uses Nb_3Sn as the superconductor has been constructed, and tests have demonstrated that this material completely shields the interior region from an external magnetic field of 8.5 kilogauss, performance that is satisfactory for use in the ATLAS beam splitter. Metallurgical studies indicate that additional heat treatment of the tube may increase the maximum field which the tube can exclude. These investigations are continuing.[1]

4. Long-Range Plan for ATLAS

Until now, most of the activities in our Superconducting Linac Development program have been concerned with solving the basic technical problems associated with the prototype booster linac and then with ATLAS. Some work of this kind will continue during the next few years, but recently we have developed a long-range plan that leads the program as a whole in a new direction. The ultimate goal of this plan is to replace the negative-ion source and tandem injector of ATLAS with a positive-ion source and superconducting linac injector.

As now conceived, there will be three phases to the work required to achieve our long-term goal: (1) during 1984 and 1985, a superconducting RF structure suitable for the acceleration of very slow-moving ions will be developed; (2) then the developmental work will be completed and tested by the construction of a prototype positive-ion injection system consisting of an electron cyclotron resonance (ECR) ion source and a prototype injector linac, and (3) finally, the prototype injector will be expanded to the size required to accelerate the heaviest ions such as ^{238}U.

In the following subsections we provide additional information concerning steps (1) and (2) of the plan for a positive-ion injector.

[1] R. C. Pardo, to be published in Proceedings of the 1984 Linear Accelerator Conference, May 7-11, 1984, Seeheim/Darmstadt.

D. CONCEPTUAL DESIGN OF A SUPERCONDUCTING POSITIVE-ION INJECTOR

It is generally agreed that the weakest link in the ATLAS accelerator will be the tandem part of the tandem-linac system. In particular, the tandem limits the ion species to the lower half of the periodic table and limits the beam current for most ions to values that are smaller than some users need. During the past year, we have studied how to remove these limitations in the most cost effective way. We conclude that the tandem should be replaced by a positive-ion source and injector.[1] Several possible combinations of this kind were considered and it was concluded that, for our needs, the optimum combination is an electron cyclotron resonance (ECR) source and a superconducting-linac injector. The ECR source has already been proven in all essentials, but the superconducting accelerating structures required for this special application would need to be developed. If successful, it is believed that the superconducting linac would be only about half as expensive as equivalent machines based on well-known room-temperature technologies.

For the proposed superconducting linac, there are two primary technical problems: (1) how to build a structure that can effectively accelerate the very slow-moving ions ($\beta < 0.01$) from the source and (2) how to overcome the influence of defocusing of the beam caused by the acceleration process. The planned solution to the first problem is to develop new accelerating structures of the kind described above in Section C.1.c., that is, short independently-phased structures that operate at an exceptionally low RF frequency. The solution to the second problem, defocusing of the slow-moving ion beam, is conceptually more complex. It involves the following elements: (1) accelerating with structures that are short enough to allow the beam to pass through before spreading much, followed by (2) focusing with short high-field superconducting solenoids, (3) minimizing the magnitude of defocusing by operating the resonators with a small synchronous phase, made possible by very short beam pulses, and (4) minimizing the impact of the defocusing by using the high charge state of the source and the large accelerating field of the superconducting resonator to rapidly increase the beam energy to a point where defocusing is easily controlled.

---

[1]L. M. Bollinger and K. W. Shepard, to be published in Proceedings of the 1984 Linear Accelerator Conference, May 7-11, 1984, Seeheim/Darmstadt.

In the barest outline, the proposed positive-ion source and injector system would consist of the following: (1) an ECR source on a 350-kV voltage platform; (2) an accelerator tube to ground potential, followed by a beam analyzer and buncher; (3) a superconducting linac formed of three different kinds of accelerating structures: resonators of the kind outlined in Section I.A.c., split ring structures with $\beta = 0.04$, and split-ring structures with $\beta = 0.06$; (4) stripper and charge-state selector at the output of the injector linac, and finally (5) injection into the existing booster linac.

The size of the injector linac depends entirely on performance requirements. Our plan is to build first a prototype linac that is just large enough to test all aspects of the new technology and then, after all developmental problems have been solved, to expand the system enough to permit ^{238}U ions to be accelerated to the energy required for injection into ATLAS. The prototype linac would be about 8 meters long, about half of the size required to accelerate ^{238}U.

Insofar as other performance characteristics are concerned, the proposed positive-ion system is satisfactory in all respects. Relative to the present tandem, we expect the following: beam current at least an order of magnitude greater; transverse emittance almost as good; longitudinal emittance somewhat better; easy energy variability; and, overall improvement in operational reliability.

E. SUMMARY OF NEAR-TERM PLANS

The assembly of the ATLAS linac will be completed and the first beams will be accelerated during 1985. Undoubtedly it will be necessary to devote a sizable effort to the study of the characteristics of the new machine. The most difficult task is likely to be the matching of the beam from the present booster linac into the ATLAS linac, and this task may require the development of new diagnostic techniques.

A related problem will be to develop techniques for tuning the booster linac when several charge states are accelerated simultaneously. This mode of operation is necessary in order to be able to form two independent beams, as planned for ATLAS.

The other main thrust of the work will be the development of the new low-frequency superconducting resonator required for the positive-ion injector. Our present concept for these resonators is outlined above in section C.1.a. It is expected that resonator modeling will be completed in 1984, and every effort will be made to complete a niobium prototype in time for testing in 1985.

V. ACCELERATOR OPERATIONS

Introduction

This section is concerned with the operation of both the tandem-linac heavy-ion accelerator 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. IV, 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 is operated as a source of energetic heavy-ion projectiles for research in several areas of nuclear physics and occasionally in other areas of science. The accelerator system consists of a 9-MV tandem electrostatic accelerator and a superconducting-linac energy booster that can provide an additional 20 MV of acceleration. Figure V-1 shows the layout of this system, which will be operated in its present form until the end of 1984, when it will be incorporated into the larger ATLAS system. In both the present and future forms the accelerator is designed to provide the exceptional beam quality and overall versatility required for precision nuclear-structure research.

Some aspects of the technology of the superconducting linac are discussed in Sec. IV.

1. Operation of the Accelerator

(P. K. DenHartog, C. E. Heath, S. L. Craig, J. M. Bogaty, G. P. Zinkann)

Accelerator operating statistics are summarized in Table V-1, and the beams accelerated during 1983 are listed in Table V-II.

In 1984, unlike 1983, it will not be necessary to schedule major blocks of down time for the purpose of reducing costs. However, some down time may be needed in late 1984 to accommodate activities connected with the ATLAS project.

During the early years of operation of the superconducting linac, the tuning of the linac and other operational procedures were carried out by the staff members who were responsible for the design and construction of the machine. These operational responsibilities have gradually been transferred to the former tandem-operation crew, so that by now a single team is responsible for operation of the whole tandem-linac system. However, the maintenance of the linac continues to be carried out mainly by members of the group who are responsible for building the ATLAS linac. This responsibility will also be gradually transferred to the operating crew.

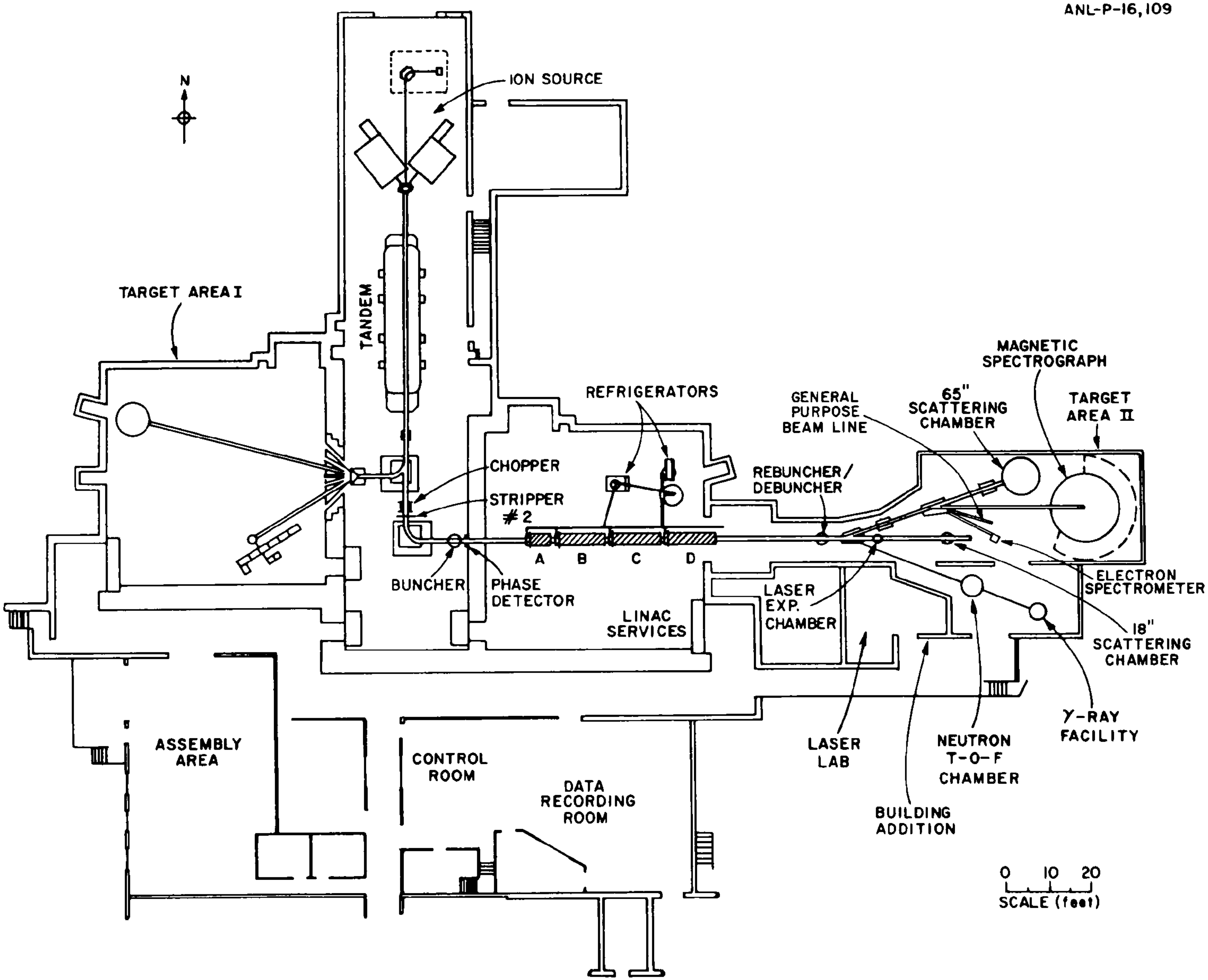

Figure V-1. Layout of the tandem-linac accelerator system.

Table V-I. Operation of the ANL tandem-linac heavy-ion accelerator.

	Fiscal Year 1983	Fiscal Year 1984*
Distribution of Machine Time (hr)		
Research		
Tandem-Linac System	3,101	4,450
Tandem (stand alone)	178	150
Tuning	469	500
Machine Studies	312	400
Unscheduled Maintenance	920	500
Scheduled Shutdown	3,780	2,760
Total (1 yr)	8,760	8,760
Distribution of Research Time (%)		
ANL Staff	50	52
Universities (U.S.A.)	39	39
DOE National Laboratories	1	2
Other Institutions	10	7
Total	100	100
Outside Institutions Represented		
Universities (U.S.A.)	14	18
DOE National Laboratories	2	2
Other	6	6

*Data derived from experience to May 1983 and projection thereafter.

Table V-II. Summary of ions accelerated by the superconducting linac in 1983. The entries labelled Q_1 and Q_2 give the charge states in the tandem and in the linac, respectively.

Particle	Q_1	Q_2	Max. Energy (MeV) Tandem	Linac
^{10}B	4	5	42.5	108
^{11}B	4	5	42.5	111
^{12}C	5	6	51.0	130
^{14}N	5	7	51.0	146
^{16}O	6	8	59.5	168
^{18}O	6	8	59.5	173
^{24}Mg	7	11	68.0	228
^{28}Si	8	13	76.5	267
^{30}Si	8	13	76.5	271
^{32}S	9	14	85.0	295
^{34}S	8	13	76.5	277
^{35}Cl	8	13	76.5	279
^{37}Cl	8	13	76.5	281
^{40}Ca	10	10	93.5	252
^{46}Ti	9	17	85.0	354
^{48}Ti	9	16	85.0	340
^{50}Ti	9	16	85.0	341
^{60}Fe	10	19	93.5	400
^{58}Ni	10	19	93.5	398
^{60}Ni	10	19	93.5	400
^{64}Ni	10	19	93.5	400

2. Status of the Superconducting Linac

The present 24-resonator booster linac was completed in 1982. During the past year there have been few changes in this system, but it has been used routinely and effectively for research. The maximum accelerating power of the tandem-linac system continues to be roughly equivalent to that of a 24-MV tandem with two strippers for projectiles in the range $25 < A < 85$.

3. Upgrading of the Linac

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

Most of the effort by the linac development group has been devoted to the ATLAS project during the past year. However, several developments connected with the booster linac are worthy of note.

a. Energy-Measurement System

The time-of-flight energy-measurement system that makes use of two beam-excited resonators continues to be refined and is increasingly useful. During the past year, there have been several occasions on which the reliability of the system has been questioned, but in each case the problem has been identified as a minor bug in the system's software or a problem with the reference energy provided by the tandem-energy analyzing system. This latter problem results from the fact that the mass spectrum of the heaviest ions is very complex after the second stripper and this can cause a false energy determination by the magnetic analyzer. By now, it is clear that the time-of-flight technique is an effective way to measure beam energy.

b. Pre-tandem Beam Buncher

During the past year, a new pre-tandem buncher has been designed, built, and put into operation. The primary new requirement on this system is that it be able to provide bunching at a frequency of 12.125 MHz in addition to the original 48.5 MHz. Also, the system should be switchable from one frequency to the other with ease.

In addition to having a completely new system of electronics, the new buncher has several features that are different from the original system: (1) the saw-tooth-like accelerating wave form across a gridded gap is generated by three harmonics rather than four. (2) both grids of the accelerating gap are driven by all three harmonics. (3) the resonance circuit is formed by a linked system of lumped parameters (condensers and copper coils) rather than by transmission lines. (4) following the approach taken at the Heidelberg tandem, the accelerating grids are mounted on cones that are designed to minimize the influence of the RF field outside of the accelerating gap. (5) a pickup probe provides information that makes it easy to tune the phases and amplitudes of the system.

The new beam buncher is now on line and, as expected, the beam-pulse width and bunching efficiency are similar to what was obtained with the original system: ~1 ns width and 75% efficiency. The advantages of the new system are: (a) the availability of two bunching frequencies, (b) the diagnostic pickup probe, and (c) greater operational reliability.

c. Extra Accelerating Section

Operating experience has shown that the primary technical problem with the linac is the fact that, over a very long period of operation, the performance of some resonators deteriorates. These units can be restored to their original performance by a simple cleaning procedure, but this work requires an unacceptable loss of running time. Our proposed solution to this problem is to have an extra accelerating section that can be perfected off line and then rapidly interchanaged with a defective on-line unit. We expect Accelerator Improvement funds in 1985 with which to fabricate the extra section.

Although the "extra" accelerator section is not yet available, the idea outlined above is being tried now by putting one of the new ATLAS sections on line. This has the dual advantage of improving the performance of the present linac and providing a complete testing of the ATLAS unit.

4. Upgrading of the Tandem

(P. K. Den Hartog, C. E. Heath, and F. H. Munson)

A large number of tasks are carried out annually with the objective of improving the performance and reliability of the tandem. We mention here only those activities of most general interest.

a. Computer Control and Monitoring (R. C. Pardo, P. K. DenHartog, and F. H. Munson)

The long-term program to control and monitor the tandem with a computer has continued during the past year. This work, which is partly motivated by the needs of the ATLAS project, consists of three distinct components, as described below.

1) The existing linac-control computer is being upgraded so that it possesses a much larger addressable memory space and improved computational speed. The hardware for this system was installed in December 1983 and is now being used routinely. The new system has one megabyte of addressable memory - a factor-of-four increase over the previous size. The installation of a high-speed cache memory will increase the average computational speed of the system, allowing significant increases in the complexity of analysis and the ability to do background development and operate the machine simultaneously.

2) The control of complex subsystems of hardware in the accelerator such as ion sources, the cryogenic system, superconducting magnets, and beam-scanning devices will be given local intelligence with microprocessors which are placed in local CAMAC crates. These microprocessors will communicate with the central PDP-11/34 over the CAMAC highway which allows the central computer to also have direct control of the units if necessary and provides a link to the outside world for higher-level calculations, manual control, and emergency warnings. The first prototype of this system is being used to control the new "west injector" ion source. The prototype system is functioning in a skeletal manner at this time. It is anticipated that the complete system for the ion source will be in place by early spring. A new cryogenic monitoring system will be implemented as the next application of this microprocessor system.

3) The control console for the ATLAS accelerator will be enlarged from the current complement of two knobs to a total of six knobs. This will allow more efficient manual control of the linac as well as control of beam-line components. The console will also contain a new color monitor overlayed with a touch-sensitive screen for more efficient control of devices in the accelerator and the beam lines. To allow user control of various features in the linac and beam lines, a smaller verison of the new console will be placed in the new data-acquisition room of ATLAS. This satellite console will be constructed after the console in the control room has been installed and debugged.

b. Terminal Lens

In last year's report, we mentioned that an electrostatic quadrupole lens had been installed in the tandem terminal with the objective of increasing beam transmission by focusing the beam after it passes through the terminal stripper. The lens has now been successfully tested. It increases beam current by about 20% for an ion species such as ^{58}Ni and is expected to cause a larger increase for heavier ions.

c. Foil Stripping

The effort to improve the lifetime of stripping foils by means of the method developed at the Japan Atomic Energy Research Institute is continuing. Our objective is to develop a reliable method for making long-lived foils that are ~3 $\mu g/cm^2$ thick. Rather little effort has been devoted to this activity during the past year because of the pressure of other work.

d. Stripping System

The tandem-linac accelerator system often makes use of two foil strippers, one in the tandem terminal and the second near the object slits of the tandem-beam magnetic analyzer. This location of the second stripper has the advantage that the analyzer selects a single charge state for injection into the linac, but the location also has two disadvantages: (1) the stripper is not at a time focus, and thus energy straggling causes the product $\Delta E \Delta t$ to be seriously enlarged and (2) the second stripping complicates the magnetic-rigidity spectrum to such an extent that the analyzer may not be able to select cleanly a single ion species.

In an effort to minimize these problems, a stripping system is being prepared for installation at the entrance of the linac. This location has the advantages that (1) stripping will occur at a time focus and (2) the magnetic-rigidity spectrum seen by the analyzer will be relatively simple. On the other hand, the linac may now accelerate several charge states, which would complicate tuning and require charge-stage selection after the linac. If these problems can be solved, however, the new stripper location may yield a substantial improvement in the quality of the output beam.

5. Ion-Source Development

(P. J. Billquist and J. L. Yntema)

This activity is aimed at developing improved negative-ion sources and specialized beams for use in nuclear-physics research with the superconducting linac.

a. Ion-Source Test Facility

The test facility continues to be used intensively and to be upgraded as required by the developmental program. Recently, a residual-gas analyzer has been added to the system. This instrument facilitates the early detection of small leaks in the system, which may have very deleterious effects on negative-ion production. The analyzer also allows the monitoring of gas (NH_3 and O_2) introduced into the source at very low partial pressures ($\sim 10^{-8}$ Torr) while the total pressure is much larger. An IBM PC computer has been installed in order to be able to monitor source parameters and performance as a function of time.

b. Hydrogen-Loading System

The new system for loading hydrogen into target material has been used extensively during the past year. The system has been used repeatedly to load hydrogen into titanium. A target of Nb loaded with hydrogen produced several μA of NbH_2^-. A technique was developed for the loading of H_2 into calcium metal, and a loaded target produced a 2.6-μA beam of CaH_3^-, which is about 5 times greater than has been reported previously.

c. Inverted Sputter Source

The modified inverted sputter source is now fully operational, and a copy of the prototype source has been made for routine on-line use in the West Injector. The new sputter source has been used to produce beams for several experiments and it performed well.

The influence of NH_3 on the operation of the source is being investigated, and the preliminary results obtained are very encouraging.

d. The SNICS Source

Our version of the Wisconsin-developed SNICS source has been put into operation and used to produce ions of $^{46,48,50}Ti$ that were used in a six-day run on the tandem-linac. For a target of natural titanium loaded with H_2, the $^{46}TiH^-$ and $^{50}TiH^-$ beams from the source were 300 nA and 200 nA, respectively, giving beam intensities of 1 and 2 pnA of Ti^{17+} on target. The source required only slight adjustment during the rather long period of operation. The SNICS source was also tested successfully with a calcium target loaded with H_2.

A system with which to investigate the influence of NH_3 gas on the operation of the SNICS source has been designed and built, the principal objective being to obtain more intense beams of calcium ions. The initial test results are very encouraging in that the NH_3 gas causes the intensity of CaH_3^- to increase greatly; the source operated stably for long periods of time.

6. Near-Term Plans

a. Accelerator Operation

In order to release the manpower required to install the experimental system for ATLAS, the present tandem-linac system will be shut down for a three-month period beginning in November 1984. As now planned, the machine will then go into operation again in its present mode for a period of about six weeks, after which there will be a second interruption of routine operation while the complete ATLAS system is tested during April 1985.

Operation of the complete ATLAS system for research will begin during the second half of 1985.

b. Linac Improvements

An upgrading of the controls of the refrigerator and cryogenic systems will be carried out in 1985. This computer-based system will make it easy to manage some rather complex and time-consuming functions that now require the continuous presence of an operator.

Accelerator-Improvement funds will be available in 1985 with which to start fabrication of the extra linac section required to implement a systematic program of upgrading the performance of on-line resonators. As outlined in section I.C.c. above, this maintenance system is being tested now by using a new linac section built for ATLAS, but this section will be available for only a few months. An accelerator section that is permanently dedicated to the maintenance task is urgently needed.

c. Tandem Improvements.

The work on computer control will continue. A new set of quadrupole magnets (provided by the ATLAS project) will be installed in the high-energy beam lines in order to be able to inject heavier ions into the linac.

As part of the ATLAS project, a new East Injector will be installed on the tandem in 1985. The main objective of this work is to improve the mass resolution that is available for beams injected into the tandem. However, the new injector may also provide other benefits such as improved bunching and increased beam transmission through the tandem.

d. Ion-Source Development

Two main investigations are planned for 1985. One is a continuation of the study of the influence of gas (e.g. NH_3 and O_2) on the production of molecular compounds of interest for acceleration. The results obtained recently suggest that this subject should be pushed further.

The second investigation will be an attempt to control the thickness of the Cs layer deposited on a sputter target and to understand the extent to which this thickness influences negative-ion production. If, by controlling the Cs thickness, one can control the surface-work function, it seems likely that the negative-ion intensity of certain elements such as Nb can be increased substantially.

7. Outside Users of the Superconducting Linac

The completion of the linac booster and its continuing refinements, as well as the increasing degree of completeness of the experimental apparatus, make the facility a very attractive one for research in precision heavy-ion research. Consequently, during 1984, outside use of the superconducting linac is becoming a major component in the national program for heavy-ion research. At present more than 2/3 of all experiments involve outside users in one way or another.

As a consequence of the involvement by outside users, we have started to implement a formal user-assistance program aimed at providing the following assistance for outside users: (1) general liaison services, (2) instruction on the characteristics of the accelerator system as a whole, (3) help in planning experiments, particularly with regard to compatibility between the user's equipment and the accelerator facility, (4) instructions on the use of particular major apparatus that is part of the ATLAS facility, (5) instruction and help with the use of computer hardware and software, (6) a well-defined mechanism for making use of ANL facilities to solve unforeseen technical problems, (7) some technical support in setting up experiments, (8) office space, and (9) a minimal level of typing service. Whereas our expected funding in FY 1985 will not allow us to provide all services at the level that we consider necessary, it is hoped that improved funding in FY 1986 will allow us to implement the outside-user program fully.

In 1983 a major change in the way that beam time at the linac is allocated was initiated. The previous Policy Advisory Committee was expanded to a Program Advisory Committee, meeting regularly every 4 months to make recommendations on individual proposals submitted for beam time at the linac. The members of this committee are Walter Benenson (MSU), Richard Diamond (LBL), John Fox (FSU), Russell Betts (ANL), and Walter Henning (ANL). The task of this committee has proven to be quite demanding since beam-time requests are currently exceeding available scheduling time by more than 50%.

In late 1983 a second workshop on experimental equipment for ATLAS was organized to provide a forum for outside-user input. The aim of this Workshop was to provide an overview of the experimental stations planned for

ATLAS, to describe the present status of each individual apparatus, to solicit final input on devices of phase I (i.e. on those that will be ready when beams from ATLAS become available at the middle of 1985), and to discuss and collect new ideas on equipment for phase II. There were short presentations on the status of the various projects, followed by some informal discussions. The presentations mainly concentrated on new equipment for target area III, but also included some descriptions of current special apparatus in area II that might also be of interest for experiments with higher-energy beams in area III.

Attendance was good, with 30 outside users from 16 institutions. A report of this meeting is being prepared and will be sent to the attendees and all other potential users to provide information on our current equipment plans and to stimulate user input.

A user manual has been completed and is being sent out to the linac users. The purpose of this manual is to provide initial information on the various questions that a user might encounter who plans to do an experiment at the linac.

The magnitude of the outside use of the accelerator during the past year may be judged from the following two lists: (1) the experiments performed by outside users and (2) the institutions represented. As may be seen from the names associated with each experiment, the university groups are by now playing a major role in an important fraction of the experiments and a dominant role in some.

a. Experiments Involving Outside Users

All experiments in which outside users participated during 1983 are listed below. The names in parentheses are Argonne collaborators.

(1) Development of a Laser-Spectroscopy Experimental Program
M. A. Finn, G. W. Greenlees, and S. L. Kaufman, University of Minnesota; D. A. Lewis, Iowa State University (C. Davids)

(2) Projectile-Target Dependence of Incomplete Fusion: Measurements of ^{14}N-induced Reactions
P. Gonthier, Hope College; F. W. Prosser, Jr., University of Kansas (G. Stephans, R. Janssens, J. Kolata, D. Kovar, K. Lesko, G. Rosner, E. Ungricht, B. Wilkins)

(3) Spectroscopy of Proton-Rich N = 81, 82, 83 Nuclei
P. J. Daly, R. Broda, Y. H. Chung, Z. W. Grabowski, J. McNeill, W. Trzaska, Purdue University; (R. Janssens, D. Radford)

(4) High-Spin States in ^{181}Ir and ^{147}Eu
E. G. Funk, U. Garg, J. W. Mihelich, A. Chaudhury, University of Notre Dame; (R. Janssens, D. Radford)

(5) Time-of-Flight Measurements of Evaporation Residues from the ^{32}S + ^{24}Mg System
J. Hinnefeld, University of Notre Dame; F. W. Prosser, Jr., University of Kansas; (J. Kolata, R. Janssens, G. Stephans, G. Rosner, B. Wilkins, D. Henderson)

(6) Deep Inelastic Scattering of ^{58}Ni and ^{12}C
D. Shapira, J. Ford, R. Auble, J. Gomez del Campo, Oak Ridge National Laboratory; S. Thornton and A. Harmon, University of Virginia (R. Betts, S. Saini, B. Wilkins, D. Henderson, S. Sanders)

(7) Electron Spectrometer Development
P. J. Daly, Z. Grabowski, M. Kortelahti, Y. H. Chung, C. Carter, J. McNeill, R. Broda, Purdue University (T. L. Khoo, R. Janssens, D. Radford)

(8) Electronic Detection of Ultra-Heavy Nuclei by Pyroelectric Materials
J. A. Simpson and A. J. Tuzzolino, University of Chicago

(9) Alpha Particle Emission from Excited Nuclei Formed in Fission Fragments
S. J. Sanders, Yale University (R. Betts, S. Saini, B. Wilkins)

(10) Fast Light Particle Emission in Fusion Reactions of ^{32}S and ^{40}Ca
C. A. Maguire, A. Ramayya, J. Hamilton, M. Barclay, W. Ma, R. Piercey, D. Watson, K. Teh, Vanderbilt University; G. Young, Oak Ridge National Laboratory (D. Kovar, D. Henderson, H. Ikezoe, R. Janssens, G. Rosner, G. Stephans, B. Wilkins)

(11) Investigation of ^{186}Hg Isomeric State
P. J. Daly, Y.-H. Chung, J. McNeill, M. O. Kortelahti, Purdue University (R. Janssens, D. Frekers, D. Radford, and T. L. Khoo)

(12) Inelastic Scattering and Reactions of Ni + Ni
R. Ledoux, M. Al-Juwair, C. Ordonez, Massachusetts Institute of Technology (R. Betts, S. Saini, I. Ahmad, B. Wilkins)

(13) Study of Direct Reaction Channels Induced by ^{28}Si on ^{40}Ca and ^{208}Pb
J. Kolata, R. Racca and R. Vojtech, Notre Dame University (D. Kovar, G. Stephans, W. Freeman, H. Ikezoe, R. Pardo, K. E. Rehm and G. Rosner)

(14) Search for Superdeformed Shapes in the Er Region
W. Kühn, University of Giessen, R. Ronningen, Michigan State University (P. Chowdhury, R. Janssens, T. L. Khoo, G. Rosner)

(15) Fusion Cross Section Behavior for $^{10}B + ^{13}C$ and $^{11}B + ^{12}C$
J. F. Mateja, J.A. Garmon, D. E. Fields, Tennessee Technical University; A. D. Frawley, Florida State University (D. Kovar, D. Henderson, H. Ikezoe, R. Janssens, G. Rosner, G. Stephans, B. Wilkins)

(16) Fission Following Fusion of Ni + Sn
W. S. Freeman, Fermi National Accelerator Laboratory (G. Rosner, K. Lesko, W. Henning, K. E. Rehm, J. Schiffer, G. Stephans, B. Zeidman)

(17) Very High Spin States in ^{147}Gd
J. Borggreen, G. Sletten, Niels Bohr Institute; R. J. Broda, Y.-H. Chung, P. J. Daly, Z. W. Grabowski, M. O. Kortelahti, and J. McNeill, Purdue University (P. Chowdhury, R. Janssens, T. L. Khoo, D. Frekers, and W. Kühn)

(18) Two Electron Titanium Wavelengths
A. E. Livingston, University of Notre Dame (H. G. Berry, J. Hardis, and W. Ray)

b. Outside Users and Institutional Affiliations

(1) Michigan State University
A. Galonsky
C.-K. Gelbke
W. G. Lynch
R. M. Ronningen
B. Tsang

(2) Purdue University
R. J. Broda
C. S. Carter
Y.-H. Chung
P. J. Daly
Z. W. Grabowski
M. O. Kortelahti
J. McNeill
W. Trzaska

(3) Notre Dame University
A. Chaudhury
E. G. Funk
U. Garg
E. J. Galvez
J. D. Hinnefeld
J. J. Kolata
A. E. Livingston
A. J. Mazure
J. W. Mihelich
R. Racca
R. J. Vojtech

(4) Vanderbilt University
M. Barclay
J. Hamilton
W. C. Ma
C. Maguire
R. Piercey
A. Ramayya
K. Teh
B. Watson

(5) Iowa State University
D. A. Lewis

(6) University of Kansas
F. W. Prosser, Jr.
V. Reinhart

(7) Oak Ridge National Laboratory
R. Auble
T. Awes
J. Ford
J. Gomez del Campo
D. Shapira
G. Young

(8) M.I.T.
H. A. Al-Juwair
R. J. Ledoux
C. E. Ordonez

(9) University of Michigan
F. Becchetti
P.Lister
R. Stern

(10) University of Minnesota
M. A. Finn
G. W. Greenlees
S. L. Kaufman

(11) University of Virginia
S. Thornton
A. Harmon

(12) Universidade de Sao Paulo
A. Szanto de Toledo
E. Szanto

(13) Institute of Nuclear Science, Grenoble, France
I. Dorion

(14) University of Giessen
W. Kühn

(15) Yale University
S. Sanders

(16) Fermi National Accelerator Laboratory
W. Freeman

(17) University of Copenhagen
J. Borggreen
G. Sletten

(18) Ripon College
D. Zei

(19) University of Chicago
I. Abella
J. A. Simpson
A. J. Tuzzolino

(20) Hope College
P. Gonthier

(21) Japan Atomic Energy Research Institute
H. Ikezoe

(22) Weizmann Institute
Z. Vager

(23) Tennessee Technical University
D. E. Fields
J. H. Garman
J. F. Mateja

(24) Florida State University
A. Frawley

c. Summaries of Major User Programs

Several groups listed in the above tables have embarked on extensive research programs that are likely to make use of the tandem-linac accelerator for several years. In order to give some indication of the extent of these efforts, the following descriptions summarize the research of groups that have been most active during the period April 1983 to March 1984.

i. The University of Notre Dame (A. Chaudhury, E. Funk, U. Garg, J. D. Hinnefeld, J. J. Kolata, W. Kaczarowski, J. Mihelich, R. Vojtech)

A group from the University of Notre Dame is currently actively associated with the program at the tandem-linac. The research program in collaboration with scientists at ANL extends into the study of the behavior of n[illegible]s-Ir region with emphasis on changes in deformation as a function of the rotational frequency. Another project concerns the study of incomplete fusion and quasielastic reactions.

During the last year a joint proposal between Notre Dame and ANL was prepared for a BGO sum-multiplicity array combined with 10-12 Compton-suppressed germanium detectors. This equipment is intended to become the gamma-ray facility for ATLAS. The scientists and the technical staff at Notre Dame (four professors, one postdoc, two students and two technicians) are concentrating on the development of the array of 56 hexagonal BGO detectors. The work includes both the design and testing of the BGO modules as well as the accompanying electronics (CAMAC-controlled discriminators, fast ADC's, etc..). The project is currently in an early phase where 6 Compton-suppressed Ge detectors and 14 elements of the BGO array are being prepared for immediate use with the first beams of ATLAS.

ii. The Purdue University Group (P. J. Daly, Z. Grabowski, Y. H. Chung, S. R. Faber, H. Helppi, M. Kortelahti, A. Pakkanen, J. McNeill, and J. Wilson)

The Purdue University group has an active program on high-spin nuclear states at the linac. The personnel currently includes two professors, one visiting scientist from Poland, one postdoc, and two graduate students. One student whose thesis was largely based on work conducted at the linac has already graduated. A second student, whose work was entirely based on linac experiments, will soon complete his thesis.

Our program uses in-beam γ-ray techniques and is directed at several aspects of nuclear structure at high spin. We are testing the validity at the Z = 64 sub-shell closure through spectroscopic studies of N = 82 nuclei close to the proton drip line. This past year a 40 μs 10^+ isomer was discovered in the ${}^{152}_{70}Yb_{82}$ nucleus which, having a half-filled proton $h_{11/2}$ shell, was predicted to have a long-lived isomer. More recently, much effort was spent on the very neutron-deficient N = 81 nuclei just above the Z = 64 closed shell. Studies in ^{186}Hg have revealed for the first time decoupled $\nu i_{13/2}$ bands with both prolate and triaxial shapes. Transitions between oblate aligned particles and prolate collective structures as a function of spin and neutron number were studied further in ^{153}Dy, ^{155}Er and ^{155}Ho. The program is conducted in close collaboration with the γ-ray group at Argonne and details may be found elsewhere in this document.

The group has also begun a project to construct a superconducting solenoid lens to be used as a conversion-electron spectrometer. The solenoid has been delivered by the manufacturer and the magnetic-field profile has been determined to be within specifications. The spectrometer is currently being assembled at Purdue and, after testing there, will be installed at Argonne late in 1984. A lens spectrometer, on loan from the University of North Carolina and Oak Ridge National Laboratory, has been prepared for on-line use in the interim period and first experiments are planned.

iii. Iowa State and Minnesota Collaboration (D. A. Lewis, J. Kumar, G. W. Greenlees, S. L. Kaufman, and M. A. Finn)

This project will use on-line laser spectroscopy to study the optical hyperfine structure of radioactive atoms. The objective is to extract information on spins, moments, and the variation of charge radii for gound states and isomers. The species under investigation will be produced by heavy-ion beams from the tandem-linac. The radioactive atoms recoil from the production target, become thermalized in a helium atmosphere, and then are transported by a liquid-nitrogen-cooled helium jet to the laser interaction region. Resonance fluorescence spectroscopy will be employed to observe the optical transitions. Essentially Doppler-free linewidths will be obtained by collimating the atoms into an atomic beam as they emerge from the helium jet. Two cooled photomultiplier tubes will detect the fluorescent light.

Tests of the helium jet have shown that the purity of the helium is an important parameter. The helium is now obtained from the boiloff of liquid He, and additional filtering with zeolite will be used. The scattered laser-light background has been reduced to a very low level by means of adjustable baffles. Tests using the laser await the final work on the helium jet; preliminary yields of radioactivities indicate that there are sufficient numbers of nuclei in the laser interaction region to perform fluorescence experiments. However, it has yet to be shown that they are in the form of free atoms.

iv. University of Kansas Collaboration (F. W. Prosser, Jr. and S. V. Reinert)

A program of measurements is pursued at the Superconducting Linac studying the energy and projectile dependence of fusion and incomplete fusion processes for light- and medium-weight heavy-ion systems. The program of measurements now includes results for reactions induced by ^{14}N, ^{16}O, ^{24}Mg, ^{28}Si, and ^{32}S projectiles. Velocity spectra of individually-resolved evaporation-residue masses produced in reactions induced by the various projectiles on targets of ^{12}C, ^{24}Mg, ^{27}Al, ^{28}Si, and ^{40}Ca were measured by means of time-of-flight techniques and compared with the expectations for a complete fusion process in order to establish whether contributions from incomplete fusion processes are present. The results indicate that at higher bombarding energies (E_{lab} > 5 MeV/nucleon) there are incomplete fusion contributions for some systems, but not for others. Our emphasis has been on the ^{24}Mg-induced reaction measurements where, in addition to the velocity measurements, we have measured the evaporation-residue cross-section behavior for the $^{24}Mg + ^{24}Mg$ systems over the energy range $100 \leq E_{lab}(^{24}Mg) \leq 260$ MeV. In previous measurements for the $^{16}O + ^{40}Ca$ and $^{28}Si + ^{28}Si$ systems a strong entrance-channel dependence in the cross-section behavior was observed where the symmetric entrance channel $^{28}Si + ^{28}Si$ showed a strongly-decreasing cross-section behavior at higher bombarding energy and no evidence in the velocity spectra for incomplete fusion contributions. The $^{24}Mg + ^{24}Mg$ system was studied to see if this behavior is typical of identical-nucleus systems in the mass region. The results are being analyzed.

The previous collaboration in the fusion measurements of very heavy systems (e.g. Ni + Sn) has come to a conclusion and the results have been published. The present efforts are directed now towards the studies outlined above, which we plan to continue during the coming year.

B. OPERATION OF THE DYNAMITRON FACILITY

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. A layout of the accelerator and experimental area is shown in Fig. V-2. 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 down to a few tenths of a nanosecond, (3) a variety of experimental apparatus for weak-interaction studies, (4) a laser-ion beam-interaction beam line where laser beams from an argon pump and a Dye laser are available coaxially and simultaneously with the Dynamitron ion beam, (5) a post-acceleration chopper system giving beam pulses of variable width from about one nanosecond to the millisecond range at repetition rates variable up to 8 MHz, (6) a scattering chamber for electron spectroscopy with electrostatic parallel-plate electron spectrometers with variable energy resolution (0.1% to a 5%) and the capability to measure electron energies up to a few keV as a function of observation angle, and (7) two general-purpose beam lines used for a variety of short-term experiments. A PDP-11/45 computer system is used for on-line data analysis and for the control of experiments.

Nuclear physics experiments described in medium-energy physics, particularly those in weak interactions and the development of a new type of tensor-polarized deuterium gas target, rely on the Dynamitron beams.

1. FUTURE DEVELOPMENTS AT THE DYNAMITRON

The first part of a program to upgrade the energy of the Dynamitron to about 5 MV was completed during 1981. An additional stage of upgrading has now been started and will continue in 1984. This new work consists of four different projects. These are (1) a new accelerator tube, (2) high-pressure gas-handling system, (3) new high-voltage rectifiers, (4) a new computer system for the Dynamitron console. Designing of parts for the new accelerator tube has started and during 1984 the tube will be assembled, installed in the Dynamitron, and reoriented to reduce sparking. A new system for handling the SF_6 insulating gas will be installed. This will allow the use of insulating gas at a higher pressure which is required for operation near 5 MV. The high-

DYNAMITRON ACCELERATOR FACILITY

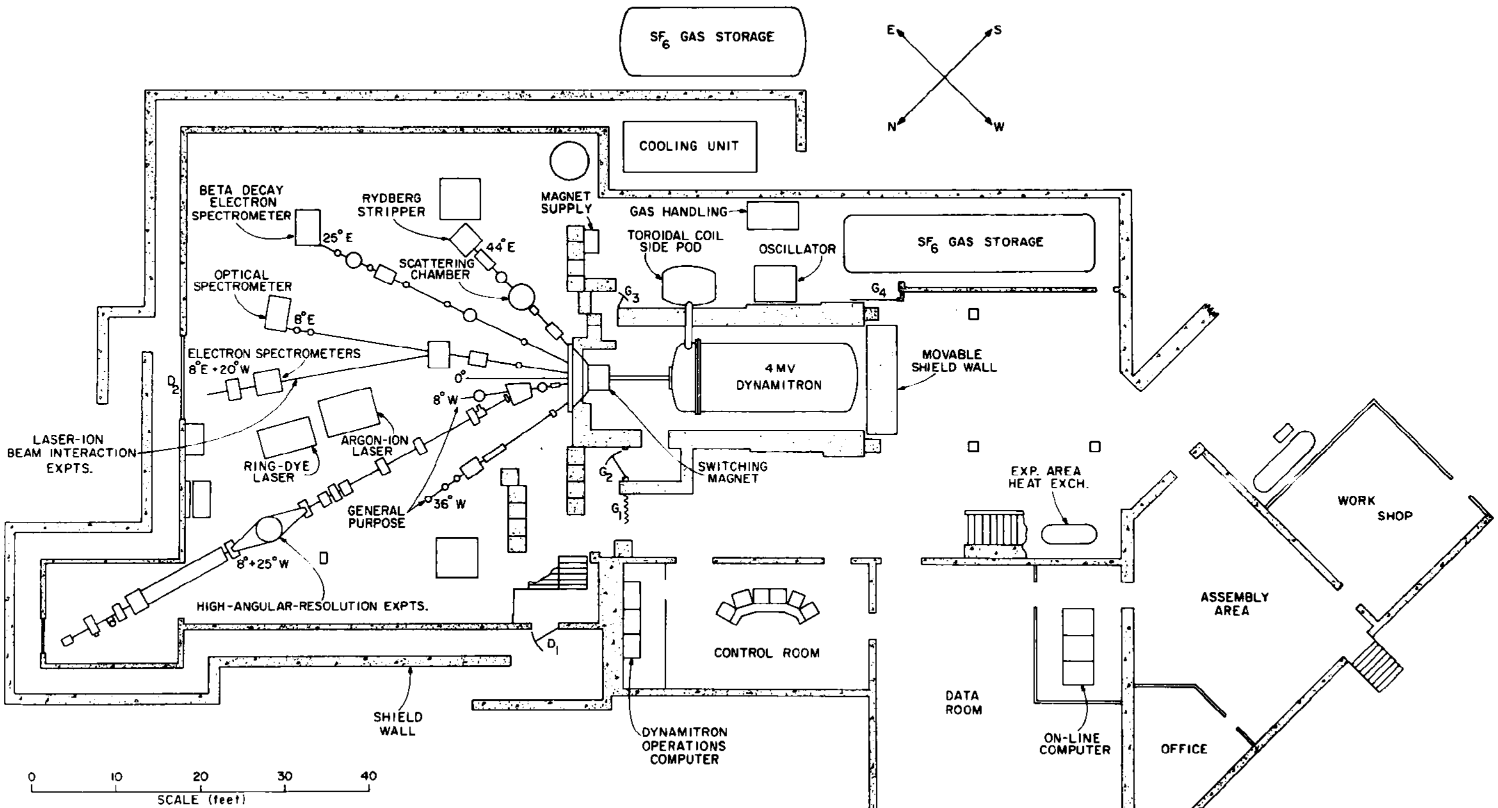

Figure V-2. Layout of the Dynamitron Accelerator Facility voltage rectifiers may have to be replaced by newer types in order to achieve reliable operation at 5 MV. The computer system currently used for Dynamitron operations will be replaced with a modern reliable system. Initially software will be developed for routine operations such as magnet calculations and data logging of machine parameters. In future fiscal years it may be desirable to replace the present lucite control-rod method of controlling and monitoring parameters in the high-voltage terminal with a system based on data transmission using a fiber-optic or infra-red light link. The new computer would then be used to monitor and control the high-voltage terminal. Ion source development will continue with emphasis being applied to improved ion optics. Computer calculations will be performed to help improve the coupling of ion sources to the accelerator tube in order to obtain better ion-beam focusing. We will also look at the feasibility of adding mass analysis and terminal pumping to the ion sources to reduce the ion loading of the accelerator tube and thus allow higher voltages. New ion sources will be studied in order to obtain new ion species. An ultra-high vacuum beam line is needed for certain experiments at the Dynamitron. Planning is proceeding for this beam line.

2. OPERATIONAL EXPERIENCE

B. J. Zabransky, R. L. Amrein, and A. E. Ruthenberg

Overall, the Dynamitron continued to perform well during the past year. Even though the number of technical staff has been reduced, the normal operating schedule continues to be twenty-four hours a day, five days a week. The Dynamitron is now usually staffed only sixteen hours a day, but can be operated by scientific personnel for the remaining eight hours. In practice this system has proved effective. If the experiment requires it, the Dynamitron can continue to run through the night, manned only by the experimenters, or upon request, the Dynamitron can be staffed twenty-four hours a day. This is normally done with outside users or others not familiar with the operation of the accelerator. Very little running was done on weekends during calendar year 1982.

During the year the accelerator was staffed a total of 3808 hours. Of this time 3021 hours (79%) were scheduled for experimental research during which a beam was provided to the experimenters 91% of the time. Machine preparation time used up 6% of the scheduled research time and machine malfunctions 3%. Scheduled accelerator improvements (including the upgrading program) and modifications used a total of 787 hours or 21% 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 385 microamperes with ion energies ranging from 0.4 to 4.1 MeV. A wide range of both atomic and molecular ions was delivered on target. They include: $^{1}H^{+}$, $^{1}H_2^{+}$, $^{2}H^{+}$, $^{1}H_3^{+}$, $^{4}He^{+}$, $^{4}He^{++}$, $^{4}HeH^{+}$, $^{7}Li^{+}$, $^{7}Li^{++}$, $^{7}Li^{+++}$, $^{12}CH^{+}$, $^{14}N^{+}$, $^{14}N^{++}$, $^{14}NH^{+}$, $^{16}O^{+}$, $^{16}OH^{+}$, $^{20}Ne^{+}$, $^{20}Ne^{++}$, $^{40}Ar^{+}$, $^{40}Ar^{++}$, $^{40}Ar^{+++}$, $^{40}Ar^{+++++}$, $^{84}Kr^{+}$, and $^{132}Xe^{+}$.

During the year a total of 55 investigators used the Dynamitron in some phase of their experimental research. Of these, 16 were from the Physics Division, 4 were from other Argonne research divisions, 19 were outside users from other research facilities, 9 were members of the Resident Graduate Student Program. In addition, 4 graduate students and 3 pre-college students participated in research at the Dynamitron. Of the scheduled time, 95% went to experiments involving members of the Physics Division, 1% to other Argonne divisions, and 4% was exclusively assigned to outside users. However, outside users collaborated in experiments that used 29% of the total available time. Undergraduate students and participants in the Resident Graduate Student Program worked on experiments that used 46% of the time.

The accelerator has been used by many research groups during 1983. It had been operating with only routine maintenance problems and relatively free of sparking at energies up to 4 MV. Sparking above 4 MV was still a problem and had been getting steadily worse because of damage inside the accelerator tube. Early in the year the machine was stripped and thoroughly inspected. The accelerating tube was found to have three of the twelve tube sections damaged. The problem is inside the tube and occurs in the sections closest to the ground end. The damage shows up as an internal resistance which causes a discharge when a high voltage is applied. Several things were done in an attempt to solve this problem without replacing the whole accelerator tube. The bleeder resistors were reconfigured to more evenly distribute the voltage and lower the voltage across the most damaged tube section. Additional spark gaps were added to help stop the damage by giving a more direct path for the sparks. After these and many other changes the Dynamitron attained 4.7 MV, but a big spark again damaged the tube. The sparking and tube damage has gradually lowered the useful operating voltage to about 3.7 MV. Sometimes it is hard to get above 3.1 MV until the machine is run for weeks and the tube damage "burns out." These problems will be solved when the new accelerating tube, which is currently under construction, is installed in early 1984. The accelerating tube now in use has been in service for 7 years. Before a new tube is constructed, the present tube was inspected in situ by the use of a specially built telescope. Visual inspection of the apertures inside the accelerator tube revealed no apparent damage.

Newer and more reliable high-voltage recitifiers were borrowed from a currently unused Dynamitron and installed in our machine. Only eighty of the required ninety-four were obtained this way. The rest will be purchased when necessary and only if operation at 5 MV requires the use of the new rectifiers. No difference in performance can be seen between the old and new rectifiers when running at the present limit of 3.7 MV.

There have been many modifications to the experimental area this year. An unused ultra-high vacuum (UHV) beam line belonging to another Argonne Division was removed and a new beam line built. This new line incorporates a quadruple lens for additional focussing and two new bending magnets. The magnets not only allow high mass-energy product ions from the Dynamitron to be used in two separate beam lines, but also allow a laser beam to be used coaxially with the ion beam and travel in either the same or the opposite directions. The first experiments using the laser-ion beam interaction beam line are currently in progress. New turbo-molecular pumps and controls were installed on this beam line with interlocks to prevent damage from vacuum accidents.

The removal of a large McPherson electron spectrometer and the UHV beam line mentioned above made available two beam lines for general-purpose use. A variety of short-term experiments were run successfully on these beam lines this year.

The development of ion sources to provide ion species of interest to specific experimental groups has proceeded slowly during the year because of the decrease in the number of technical staff. A beam of Li^+ can now be produced easily and was used many times during the year. With only a minor modification, it is hoped that a Be^+ beam can be produced from the same source. A Penning ion source was modified to accept cathodes made of Si in order to produce a Si^+ beam. This was run on the ion source test accelerator but produced no useful Si^+ beam. Efforts to improve the filament life in the duoplasmatron ion source by use of special filaments manufactured for other purposes has shown some encouraging signs. More work with different configurations will continue to see if these are a feasible alternative to the currently used filaments.

3. UNIVERSITY USE OF THE DYNAMITRON

B. J. Zabransky

The Argonne Dynamitron continues to be a valuable research facility for scientists from outside institutions. It is not only the accelerator itself that attracts outside investigators but also the unique associated experimental equipment as well as the on-going research program being conducted at the Dynamitron.

Most visiting scientists chose to collaborate with local investigators on problems of common interest. A few, however, worked as an independent group. Some came for a one-time-only experiment, but most are participants in research programs that have spanned a period of several years.

During the year nineteen scientists came from fourteen outside institutions to use the Dynamitron. They came from six states and five foreign countries. They participated in experiments that used 29% of the time scheduled for research. A list of those institutions from which users of the Dynamitron came during 1983 is given below. The list includes the name of the institution, the title of the research project, and the names of the principal investigators. The names of their Argonne collaborators are enclosed in parentheses.

(1) University of Chicago
Laser Resonant Fluorescence Measurement of Fine and Hyperfine Structures of Li^-
I. Abella, (H. G. Berry)

(2) University of Brussels, Belgium
Alignment Measurements of Foil-Excited Hydrogen Rydberg States
J. C. de Haes, (H. G. Berry)

(3) Fermi National Accelerator Laboratory
Direct Capture in the $^{27}Al(p,\gamma)$ and $^{19}F(p,\gamma)$ Reactions
A. Elwyn, M. Wiescher,* G. Hardie,† R. E. Segel‡

(4) Fudan University, Shanghai, China
Alignment Measurements of Foil-Excited Hydrogen Rydberg States
Y. Hui, (H. G. Berry)

(5) Marquette University
Radiation Damage of Covalent Crystal Structures
L. Cartz, A. Gowda, F. G. Karioris, T. Ehlert and M. Snow

(6) Millersville State College
The Study of Foil-Excited Fast Rydberg Atoms
P. Cooney, (E. P. Kanter, A. Minchinton and B. J. Zabransky)

(7) Northwestern University
Direct Capture in the $^{27}Al(p,\gamma)$ and $^{19}F(p,\gamma)$ Reactions
R. E. Segel, G. Hardie,† M. Wiescher,* and A. J. Elwyn§

(8) Japan Atomic Energy Research Institute, Japan
A Study of Carbon Foil Lifetimes
S. Takeuchi, (P. Den Hartog)

(9) Ohio State University
Direct Capture in the $^{27}Al(p,q)$ and $^{19}F(p,\gamma)$ Reactions
M. Wiescher, G. Hardie,† R. E. Segel,‡ A. J. Elwyn,§ and (W. Ray)

(10) Oxford University, England
Proton-Induced Si K-Shell Ionization Studied with Auger Electron Measurements under Channeling Conditions
E. Johnson, H. Kudo,|| (D. Schneider, E. P. Kanter, and P. W. Arcuni)

(11) University of Texas
Simultaneous Laser- and Ion-Beam Excitation of a Na Beam
C. F. Moore, P. Seidel, (D. Schneider, H. G. Berry, V. Pfeufer and W. Stöffler)

---

*Ohio State University.
†Western Michigan University.
‡Northwestern University.
§Fermi National Accelerator Laboratory.
||University of Tsukuba.

(12) University of Tsukuba, Japan
Proton-Induced Si K-Shell Ionization Studied with Auger Electron Measurements under Channeling Conditions
H. Kudo, E. A. Johnson,* (D. Schneider, E. P. Kanter, and P. W. Arcuni)

(13) Weizmann Institute, Rehovot, Israel
The Post-foil Interaction in the Foil-induced Dissociation of 3.25-MeV CH^+
I. Plesser and Z. Vager (E. P. Kanter)

(14) Western Michigan University
Direct Capture in the $^{27}Al(p,\gamma)$ and $^{19}F(p,\gamma)$ Reactions
G. Hardie,† R. E. Segel,‡ M. Weischer,¶ and A. J. Elwyn||

---

*Oxford University.
†Western Michigan University.
‡Northwestern University.
§Ohio State University.
||Fermi National Accelerator Laboratory.

The Resident Graduate Student Program is open to students that have finished their course work and passed their preliminary examinations. They come to Argonne to perform their Ph.D. thesis research. Nine members of this program worked at the Dynamitron during 1983. Altogether they participated in experiments that used 46% of the time allotted to research. Those who used the accelerator are listed below, together with their home university and their local thesis advisor.

(1) P. W. Arcuni, University of Chicago
H. G. Berry, advisor

(2) J. Camp, University of Chicago
G. T. Garvey, advisor

(3) B. Filippone, University of Chicago
C. N. Davids, advisor

(4) J. Hardis, University of Chicago
H. G. Berry, advisor

(5) A. R. Heath, University of Chicago
G. T. Garvey, advisor

(6) M. Kroupa, University of Chicago
G. T. Garvey, advisor

(7) D. Neek, University of Illinois at Chicago
H. G. Berry, advisor

(8) W. Stöffler, Free University of Berlin
D. Schneider, advisor

(9) D. Work, California Institute of Technology
G. T. Garvey, advisor

In addition, the following graduate students and pre-college students have participated in research based at the Dynamitron.

Graduate Students:

(1) E. Dehm, Lawrence University
H. G. Berry, advisor

(2) P. Seidel, University of Texas
D. Schneider, advisor

(3) P. Simmons, DePaul University
R. Cooke, advisor

(4) G. Zapalac, University of Chicago
H. G. Berry, advisor

Pre-College Students:

(1) B. Hartmann, Hinsdale Central High School
E. P. Kanter, advisor

(2) P. Meyer, Lyons Township High School
H. G. Berry, advisor

(3) C. Meyers, Lyons Township High School
E. P. Kanter, advisor

ATOMIC AND MOLECULAR PHYSICS RESEARCH

Introduction

The Atomic Physics research in the Physics Division currently consists of the following five ongoing programs:

(1) Photoionization-photoelectron research (J. Berkowitz),

(2) High-resolution laser-rf spectroscopy with atomic and molecular beams (W. J. Childs and L. S. Goodman),

(3) Photon interactions involving fast ions (H. G. Berry and L. Young),

(4) Interactions of fast atomic and molecular ions with solid and gaseous targets (E. P. Kanter, Z. Vager, W. Koenig, and D. S. Gemmell,),

(5) Theoretical atomic physics (K. T. Cheng).

The programs on ion-photon interactions and fast-ion interactions have been expanded in scope and size with the addition of two young staff members, L. Young and W. Koenig. In addition, the long-standing close collaboration between our Atomic Physics program and Prof. Z. Vager of the Weizmann Institute, Israel, has been further recognized and solidified with Prof. Vager's appointment to a part-time Senior Scientist position on the Physics Division's staff. Dr. Vager's work in the near future will concentrate mainly on the development and use of sophisticated, 2-dimensionally position-sensitive, proportional counters with good timing characteristics. These detectors are expected to open up new areas in the study of foil-induced fragmentation of fast molecular ions, since the final momenta of all fragments from each dissociating molecule will be measurable with high precision.

The Dynamitron continues to be the mainstay of our accelerator-based Atomic Physics program. It is presently being upgraded and plans are underway to install a modern on-line computing system to be used for data acquisition, experiment control, data analysis, and general computing.

The ATLAS accelerator is scheduled to come on-stream in 1985 and it is our intention to provide and equip a beam-line on this facility for use by the national atomic physics community.

VI. PHOTOIONIZATION-PHOTOELECTRON RESEARCH

Introduction

Our goal is to understand the electronic structures of atoms and molecules, and their ions, by observing the interaction of vacuum ultraviolet radiation with various species and interpreting the dynamical results of this interaction. We have also embarked upon a direct study of molecular-ion properties by examining the decomposition of these ions induced by ultraviolet laser light. Our studies involve fixed and variable wavelength photoelectron spectroscopy, photoionization mass spectrometry and laser-induced photodissociation spectroscopy.

This past year, our photoionization mass spectrometric studies have concentrated on open-shell atoms, in particular F, Cℓ and Br. We have shown in the case of Cℓ that an ab initio photoionization calculation using diagrammatic many-body theory is in general agreement with our data, but misses one complete Rydberg series. The atomic fluorine experiment yielded two significant results.

1) All the autoionization lines were narrow, analogous to the previously known behavior in neon, but differing from chlorine and argon. These results were suggestive of an important generalization regarding the proximity of unfilled "d" orbitals and the strength of the discrete-continuum interaction governing autoionization widths.

2) The most intense autoionization feature in our spectrum had previously been reported to be absent in photographic absorption. In order to rationalize these two observations, we have suggested that super-radiance or laser action was occurring.

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 multi-electron 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, possible side reactions in a magnetohydrodynamic generator and reactions in interstellar clouds. 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 photoelectron spectra of high-temperature species in molecular beams, and the other has on occasion 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.

The experiment involving UV laser photodissociation of molecular ions has progressed to the point where photofragment signals can be readily detected, without long searches. The magnetic mass spectrometer is now being dedicated to this work.

A new, more powerful excimer laser was acquired and put into operation (after overcoming some problems) in the experiment on photodissociation of molecular ions. This laser has much higher pulse energy and more pulses/sec. The former should enable us to accept the loss incumbent upon use of a Raman shifter, while the latter permits more rapid acquisition of data. A Raman shifter has also been constructed, but not yet tested with the new laser.

The laser interaction region has been moved upstream, and the ion focussing system rebuilt accordingly, in the hope of achieving better angular resolution of photofragments. With this modification, we hope to sort out more unambiguously the angular and recoil energy effects.

In the atomic photoionization experiments, an important practical achievement was the development of a vacuum system that could handle atomic and molecular fluorine. Another aspect of this research was the development of a wall coating to prevent recombination of atomic fluorine.

Progress on individual experiments is detailed below.

a. Photoionization of Atomic Chlorine (B. Ruscić, J. P. Greene, and J. Berkowitz)

A year ago, we had just obtained our first results on this atom, with 0.28 Å resolution. These results were subsequently verified and analyzed, and published as a letter. Since then, we have re-measured much of the spectrum with 0.14 Å resolution (FWHM), enabling us to resolve more of the higher Rydberg series members. In addition, we have obtained data for the narrow series with 0.07 Å resolution, in an attempt to observe the natural width of these resonances. We are planning to publish this information in a comprehensive paper describing photoionization behavior in the halogen atoms, all of which have now been studied in this laboratory.

b. Photoionization of Atomic Fluorine (B. Ruscić, J. P. Greene, and J. Berkowitz)

A completely independent pumping system had to be constructed for fluorine, since tygon tubing and a liquid N_2 trap would not work. An all-metal system with a helium cryopump was designed, and is functioning reasonably well. The wall coating which was successful for atomic chlorine proved inadequate for atomic fluorine, but one appropriate for fluorine was found. The rationale for studying atomic fluorine came from earlier experiments on atomic chlorine and the noble gases. In Ar, Kr, and Xe, two autoionizing series are observed, a broad "d" Rydberg series and a narrow "s" Rydberg series. In Ne, both are extremely narrow. Our study on atomic chlorine (above) revealed the presence of broad "d" and narrow "s" series, although the overall spectrum was more complex than those of the closed shell atoms. We were interested in the widths of these series in atomic fluorine, and found that they were all indeed narrow, limited only by our instrumental resolution (see Fig. VI-1). On this basis, and some examination of the literature, we have concluded that "first row" atoms differ characteristically in their autoionization behavior from heavier atoms. We suggest that this difference comes about because the wave function of the Rydberg atom must take into account polarization of the core. In perturbation theory, this is achieved by including other configurations. A particularly effective configuration because of its low energy of excitation and spatial distribution is a "d" orbital of the same principal quantum number m as the mp^n core. First row atoms cannot avail themselves of such orbitals, and hence their "d" resonances are narrow. Our hypothesis can be tested when the complex many-body theories are dissected and the essential elements contributing to peak widths are extracted, but this has not yet been done.

An unexpected bonus in this study was the observation that the most intense autoionization resonance in our spectrum was not anticipated to be there at all, since it had been sought and pointedly noted to be absent in an earlier photographic photoabsorption study of atomic fluorine (Fig. VI-2). In order to explain these two paradoxical observations, we have suggested that

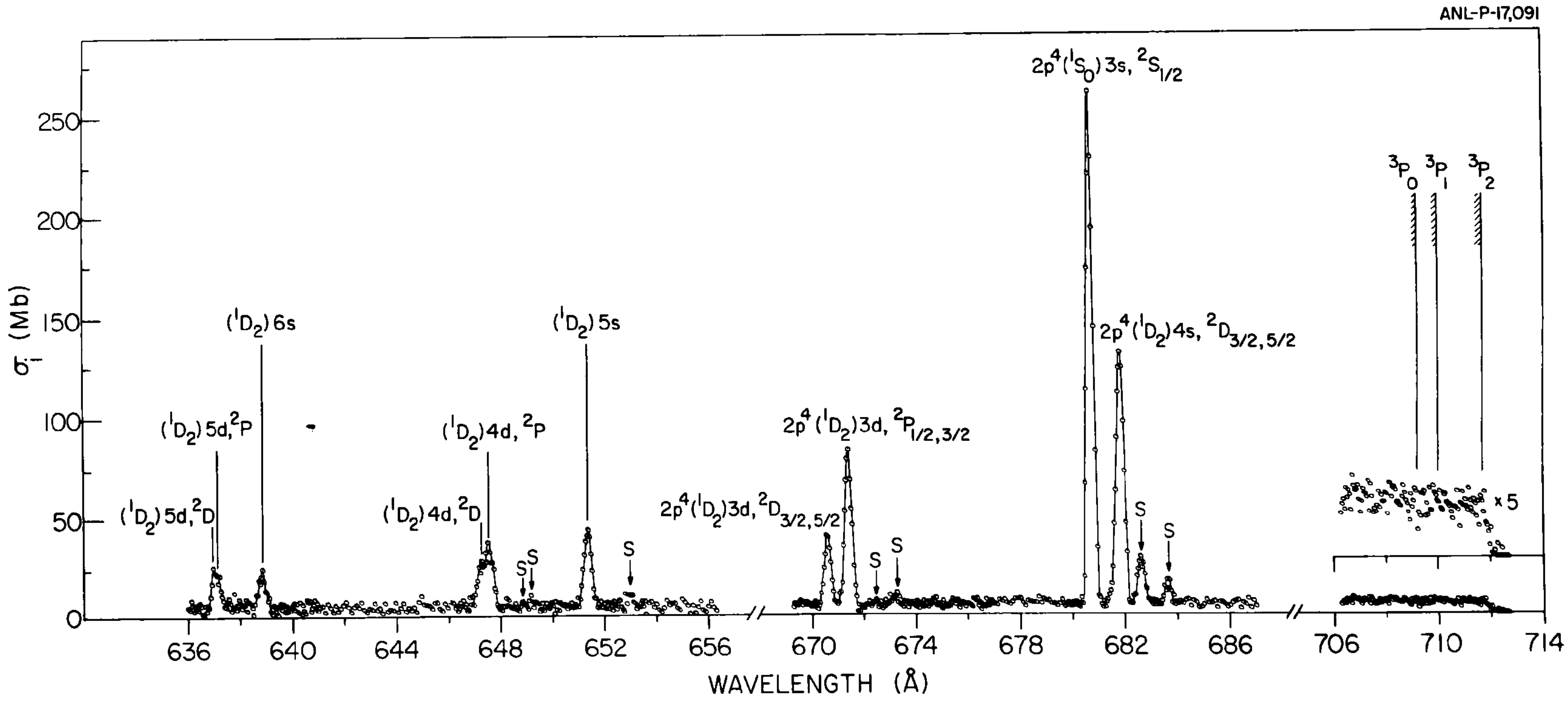

Figure VI-1. Photoionization yield curve of atomic fluorine from 636 Å to the ionization threshold. Optical resolution is 0.28 Å (FWHM). No structure was observed in the deleted sections, which were scanned more rapidly. Satellite absorptions from the excited $^2P_{1/2}$ state are denoted by S. The widths of all the peaks are instrumentally limited.

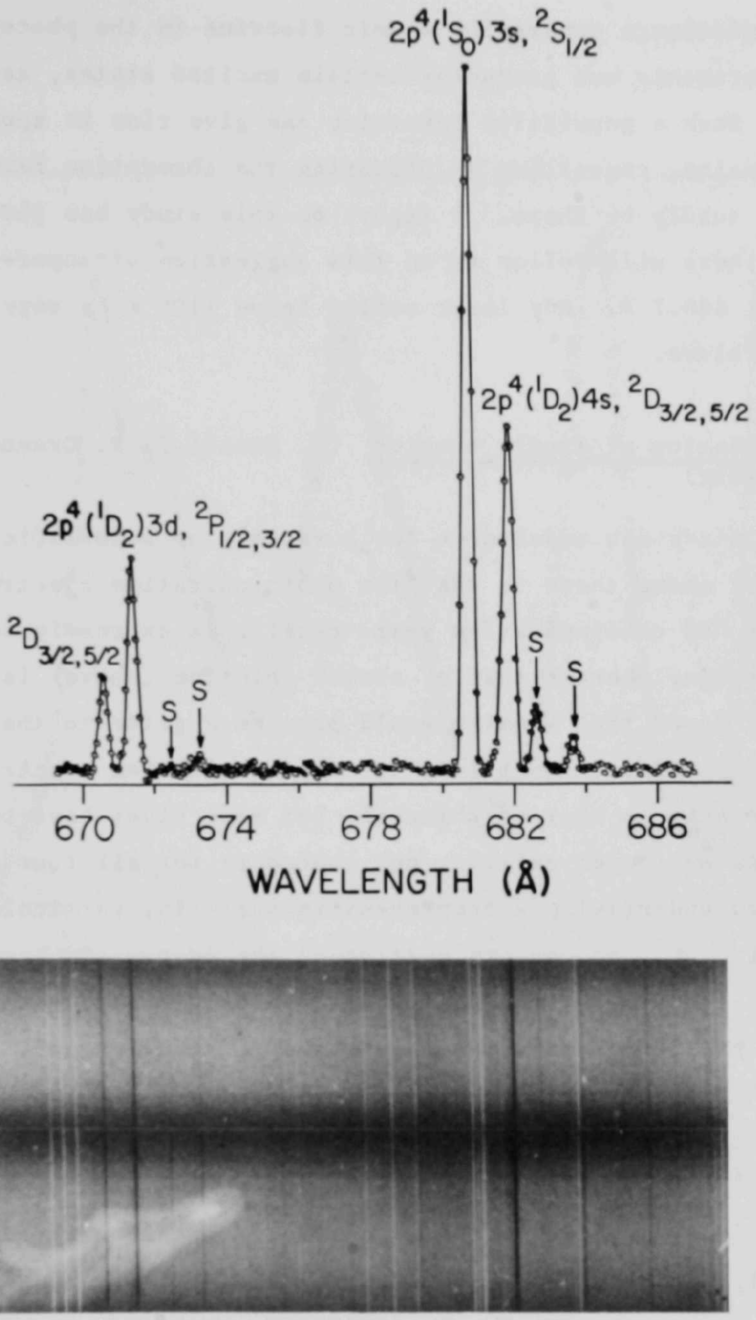

Figure VI-2. A portion of Fig. VI-1, aligned in wavelength with a photographic absorption spectrum of atomic fluorine obtained earlier by R. E. Huffman et al. at Air Force Cambridge Research Lab. Note that the most intense autoionization peak is absent as a photoabsorption, although the other strong autoionization lines have their counterparts in the photoabsorption spectrum. We thank Dr. R. E. Huffmann for permission to reproduce his absorption spectrum.

the microwave discharge generating atomic fluorine in the photographic absorption experiments was producing certain excited states, as well as the ground state. Such a population inversion can give rise to spontaneous and stimulated emission, cancelling or obscuring the absorption feature which otherwise must surely be there. A report on this study has just appeared and we hope that others will follow up on this suggestion of super-radiance or laser action at 680.7 Å. Any laser action below 1100 Å is very unusual and difficult to achieve.

c. Photoionization of Atomic Bromine (B. Ruscić J. P. Greene, and J. Berkowitz)

This study was undertaken for a variety of scientific reasons. Perhaps foremost among these is that the photoionization spectrum of atomic iodine which we had obtained a few years earlier is extremely complicated and difficult to assign, whereas that of atomic chlorine (above) is relatively simple. It was hoped that bromine would provide a guide to the proper interpretation of iodine. In brief, the photoionization spectrum of atomic bromine is more akin to that of chlorine, but some clues have been forthcoming. As mentioned earlier, now that data for all four halogens are available we are undertaking a comprehensive analysis, particularly with the contribution of G. L. Goodman, to understand the systematic increase in complexity with the size of the halogen. Some preliminary comparisons are presented in a paper on bromine, now accepted for publication.

d. Photoelectron Spectrum of B_2O_2 (B. Ruscić, L. A. Curtiss,* and J. Berkowitz)

B_2O_2 is a very stable molecule, isoelectronic with the more familiar C_2N_2 (cyanogen), but it can only be produced in equilibrium conditions at rather high temperatures. We have succeeded in obtaining the photoelectron spectrum at 1500° K (see Fig. VI-3). Prior to our study, sparse and inconclusive evidence was available regarding the geometrical and electronic structure of B_2O_2. The combination of detailed *ab initio* calculations of various alternative structures and their predicted spectra with the experimental spectrum has conclusively established the O=B-B=O $D_{\infty h}$

*Chemical Technology Division, ANL.

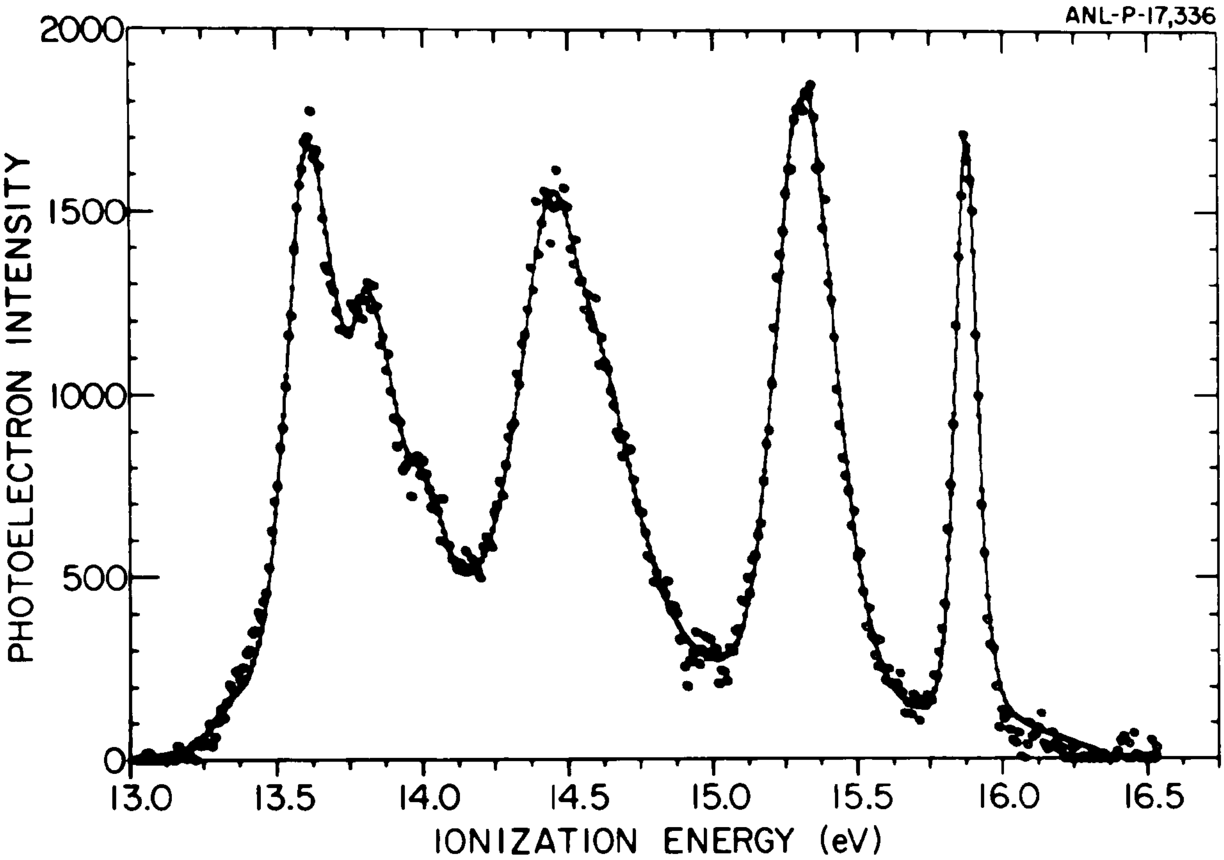

Figure VI-3. Experimental He 1 photoelectron spectrum of B_2O_2, with H_2O impurity and linear background substracted.

o - reduced experimental points

Smooth line - polyatomic Franck-Condon function fitted to the data by least squares. The derived parameters from this fitting determine the change in geometry accompanying each ionization.

structure. The analysis has proceeded further to establish the orbital sequence (which differs from that of C_2N_2) and the change in geometry when each of the four ionic states is formed. This has been accomplished both by ΔSCF *ab initio* calculations and a complex Franck-Condon fitting of the experimental spectrum, also shown in Fig. VI-3.

e. UV-Laser Photodissociation of Molecular Ions (R. E. Kutina, A. K. Edwards, R. S. Pandolfi, and J. Berkowitz)

The preliminary results given a year ago for this experiment have been improved significantly. In two instances, it has altered the conclusions. We had previously reported that neither ND^+ nor D^+ was observed as a photofragment from ND_2^+, but now we have detected ND^+ and obtained its kinetic energy release spectrum. Our earlier data on O^+ fragments from OD^+, based on poorer statistics, implied that a two-photon process was necessary to explain these results. The improved measurements, together with a study of the product intensity as a function of laser power, have demonstrated that a one-photon process is occurring. The first completed results have been submitted for publication.

VII. HIGH-RESOLUTION LASER-rf SPECTROSCOPY WITH ATOMIC AND MOLECULAR BEAMS

Introduction

The systematic, high-precision study of the hfs of $4f^N6s^2$ configurations of neutral rare-earth atoms was continued through much of the first half of 1983. A number of levels in ^{167}Er, $^{161,163}Dy$, ^{159}Tb, and ^{169}Tm were studied to supplement the measurements in ^{165}Ho done last year. A great deal of information was also collected on highly excited states. Isotope shifts were studied in $^{161,163}Dy$ and ^{167}Er for a number of optical lines and the J- and term-dependence of the shifts analyzed. Three papers on the hfs studies and two on the isotope-shift measurements were accepted for publication.

Design and construction of a combined rf and d.c.-electric-field assembly required for molecular electric-dipole moment measurements continued during the atomic experiments just described. This design was not trivial, since it was crucial that the rf field be limited to the central part of the d.c. field, and that both be completely shielded from the Earth's magnetic field. On completion, the apparatus was successfully used in a novel adaptation of the molecular-beam, laser-rf double-resonance method to measure the dipole moment of the electronic X $^2\Sigma^+$ ground state of CaF. The result, together with a new measurement by a microwave-rf method of the CaCl dipole moment, constitute the only dipole moments known for the entire alkaline-earth monohalide family of radicals.

a. Hyperfine Structure of the $4f^{12}6s^2$ ^3H and ^3F Terms of ^{167}Er I by Atomic-beam, Laser-rf Double Resonance (W. J. Childs, L. S. Goodman, and V. Pfeufer)

The laser-rf double-resonance technique was used to measure the hfs of all six levels of the $4f^{12}6s^2$ ^3H and ^3F terms of ^{167}Er I (no other levels of this configuration in Er I have so far been identified). Extraction of the $\langle r^{-3}\rangle$ hfs radial integrals from the new (1 part in 10^6 precision) measurements can only be done crudely at the present time because of the deplorably incomplete state of knowledge of the electronic structure of Er I. Nevertheless, the $\langle r^{-3}\rangle$ values obtained exhibit some LS-term dependence and show that the present hfs theory, while able to account for the dipole hfs, is not able to account satisfactorily for the quadrupole hfs. A paper on this work has just been published in Phys. Rev. A 28, 3402 (1983).

b. Hyperfine Structure in $4f^N6s^2$ Configurations in ^{159}Tb, ^{161,163}Dy, and ^{169}Tm (W. J. Childs, H. Crosswhite,* L. S. Goodman, and V. Pfeufer)

The double-resonance method was used to make similar measurements in ^{159}Tb, ^{161,163}Dy, and ^{169}Tm. Several new optical lines and atomic levels were discovered as a byproduct of the work. In contrast to the ^{167}Er case just mentioned, it was possible to extract rather precise $\langle r^{-3} \rangle$ values from this work. The $4f^N6s^2$ results for all rare-earth atoms (including all previous measurements) are summarized and compared with the *ab initio* theory. The theory is found to be in good agreement with experiment for the magnetic-dipole hfs, but appears to overestimate the relativistic parts of the electric-quadrupole hfs interaction. The work has stimulated new, much more sophisticated *ab initio* calculations involving relativistic treatment of many configurations simultaneously in an effort to obtain better agreement with experiment. A paper describing the experimental work was published in J. Opt. Soc. Am. B 1, 22 (1984).

---

*Chemistry Division, ANL.

c. Crossed-second-order Effects in the Isotope Shift of the Ground Configuration $4f^{12}6s^2$ of Er I (V. Pfeufer, W. J. Childs, and L. S. Goodman)

This study measures the isotope shift of selected optical lines of Er I, and analyzes the J- and term-dependence found. The work was published in J. Phys. B 16, 557 (1983).

d. J-dependence of the Isotope Shift in the Ground Term of Dysprosium I (V. Pfeufer, W. J. Childs, and L. S. Goodman)

This work describes the J-dependence observed in the isotope shift of selected optical transitions in ^{161,163}Dy I. It was published in J. Opt. Soc. Am. B 1, 34 (1984).

e. Electric-dipole Moment of CaF (X $^2\Sigma^+$) by Molecular-beam, Laser-rf Double-resonance Study of Stark Splittings (W. J. Childs, L. S. Goodman, U. Nielsen, and V. Pfeufer)

The normal molecular-beam, laser-rf double-resonance method was modified and extended in the present experiment to make possible the measurement of the electric-dipole moments of diatomic molecular radicals. The modification involves requiring the radiofrequency transitions to occur in a homogeneous d.c. electric field instead of in a field-free region. The molecular levels are split and distorted by the interaction of the dipole moment with the field so that observation of the Stark splittings in a known field permits measurement of the dipole moment. The work was complicated by two problems:

(1) considerable ingenuity had to be used to prevent the occurrence of rf transitions near the edges of the d.c. electric field (where it is weaker), and (2) the effective d.c. field could easily be weakened by beam deposits on the field plates. Figure VII-1 shows how one radiofrequency hyperfine transition in the N = 2, v = 0 rovibrational state of the X $^2\Sigma^+$ ground state splits into 8 components in the electric field. The parameter X is proportional to $(\mu E)^2/B$, where μ is the electric-dipole moment, E is the electric-field strength, and B is the molecular rotation constant. The experimental points (circles show that X = 130.0. From this and the knownb field strength the value obtained for the dipole moment of the X $^2\Sigma^+$ (v = 0) electronic ground state of CaF is 3.07(7) Debye. Only two other moment values (also reported in 1983) exist for the entire alkaline-earth monohalide family, and already it is clear that the only semi-theoretical moment estimate available is off from experiment by a full order of magnitude. Clearly, measurements of this type, combined with the precise hfs results we have reported earlier, will be of great importance in attempts to understand the structure of the simplest of the open-shell diatomics. The results were published in J. Chem. Phys. 80, 2283 (1984).

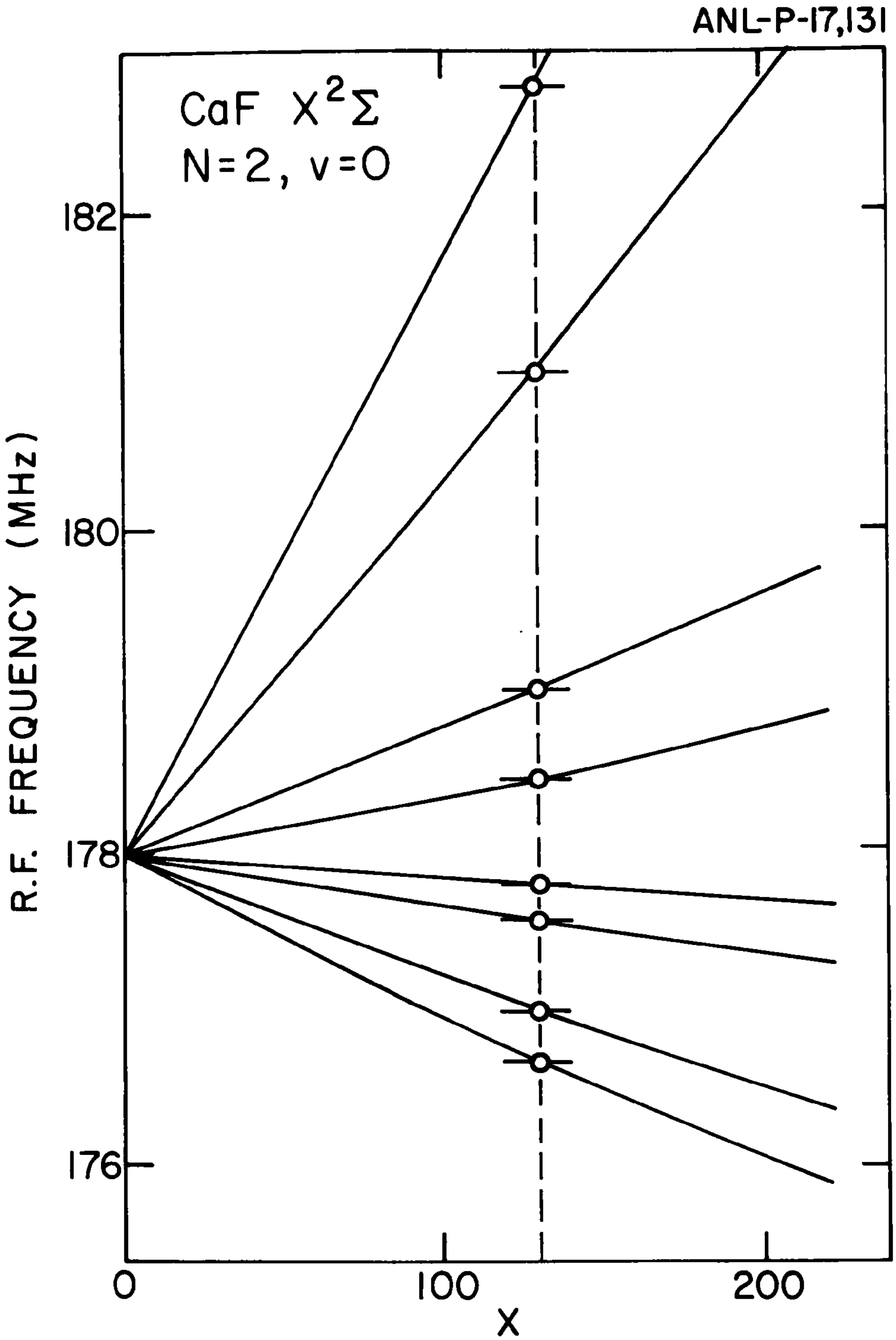

Figure VII-1. Electric-field dependence of the Stark components of the v = 0 (X-state) rf transition N, J, F = 2, 2.5, 3 ↔ 2, 1.5, 2. The sloping curves give the calculated resonance frequencies plotted against the parameter X which is proportional to μ^2E^2/B. The points show where the resonance frequencies observed for E = 747.7 volts/cm are consistent with the calculated curves. The deduced result X = 130.0 MHz, together with the measured electric-field strength, gives the CaF (v = 0) X $^2\Sigma^+$ dipole moment.

VIII. PHOTON INTERACTIONS INVOLVING FAST IONS

Introduction

Our work in atomic structure using fast-ion beams is aimed principally at improving our understanding of relativistic and quantum-electrodynamic effects in heavy ions. We study systems with only a few (1--4) electrons to test precise ab initio calculations, and we study many-electron systems to test more general relativistic calculations (e.g., relativistic Hartree-Fock). In atomic collision studies, we analyze the alignment and orientation production of excited states in fast ion-solid interactions. Total excitation probabilities are also measured and studied in terms of secondary-electron production and molecular coherence effects. Optical techniques are used to study the dynamics of fast molecular and atomic ions in solids, and at surfaces. Resonant laser excitation of fast ions is being used to study in detail relativistic fine structures and hyperfine structures of both positive and negative ions of low nuclear charge. Research using lasers operating in the ultra-violet is also part of this program.

Our program consists of investigations of the structure and dynamics of atomic ions principally using photon detection techniques. The experiments involve fast ion beams produced at either the Tandem-Linac accelerator (50--500-MeV ion energy) or the Argonne Dynamitron accelerator (0.5--4.5-MeV ion energy) or a low energy "test-bench" facility (0.02--0.12-MeV ion energy). Laser excitation of the fast beams is being introduced to study atomic structure and hyperfine structures principally of low ionization stages.

In 1983, the Tandem-Linac accelerator was used to study (foil-excited) spectra of highly ionized Titanium and Nickel using a normal-incidence spectrometer fitted with a channelplate detector at the exit slit.

Experiments at the Dynamitron and "Test Bench" facilities continued our studies of the foil interaction process. The polarization emissions of light from highly excited Rydberg states in hydrogen and one-electron helium were measured to investigate the shapes of wave functions produced on leaving the foil.

Our fast-beam/laser interaction studies have begun with attempts to study laser-induced fluorescence from excited states of hydrogen, Li^-, and neon. The program has involved the construction of new beam-lines at the Dynamitron and the Test bench facility.

In November 1983, Linda Young became an Argonne staff member and joined the group principally to study fast-beam laser interactions. This part of the program is also a collaborative work with Drs. O. Poulsen and T. Anderson, of Aarhus, Denmark, under a joint NATO exchange grant.

a. Lamb Shifts and Fine Structures of n = 2 in Helium-like Ions
(H. G. Berry, J. E. Hardis,*, A. E. Livingston,†, D. Zei‡ , P. Somerville and W. J. Ray)

Following our successful calculations and experiments in silicon, sulfur and chlorine of the 1s2s $^3S_1$ - 1s2p $^3P_{0,2}$ transition wavelengths, we have continued this work in several directions:

(a) To enchance our detection efficiency we have installed a channelplate detector at the exit slit of our normal incidence monochromator. This is essential for the reduced beam intensities obtainable for the heavier, faster ion beams at the Tandem-Linac accelerator. A second channelplate detector has also been tested. This one should overcome the nonlinearities in position resolution of the standard resistive anode type. It consists of a wedge-and-strip type anode whose linearity should depend essentially on the accuracy of inscribing very thin triangles directly on the anode. A preliminary version has been made and tested. Tests are continuing.

A third type of position-sensitive detector involving VLSI technology or a multi-anode array is also under investigation:

(b) Initial measurements have been made on foil-excited titanium and nickel beams at the Tandem-Linac. The titanium results give a preliminary measurement of the n = 2 transitions, but further measurements are needed for improved precision. Nickel spectra obtained with 365-MeV nickel beams showed many new yrast transitions in 4- and more electron nickel ions, but the presently available Linac beams are too low in energy to permit the study of the 2-electron spectrum in any detail.

---

*University of Chicago, Chicago, IL.
†University of Notre Dame, South Bend, IN.
‡Ripon College, WI.

b. High-spin States in Neon (J. E. Hardis,* A. E. Livingston,† L. J. Curtis,‡ and H. G. Berry)

We have followed up our previous measurements in doubly-excited systems of ions of three and four electrons. We have made precision measurements of the quartet $1s2s2p\ ^4P - 1s\ p^2\ ^4P$ and quintet $1s2s2p^2\ ^5P - 1s2p^3\ ^5S$ transitions of three- and four- electron neon respectively. We were able to use 8-MeV doubly-charged ions from the Dynamitron for these experiments. The wavelengths, fine structure, and lifetimes have been compared with several new relativistic theories. They agree reasonably well, particularly with the correlated relativistic Hartree-Fock calculations of Cheng.

---

*University of Chicago, Chicago, IL.
†University of Notre Dame, Notre Dame, IN.
‡University of Toledo, Toledo, Ohio.

c. Optical Measurements of Molecular-Ion Fragmentation (H. G. Berry, L. Engstrom,* S. Huldt,* and I. Martinson*).

We have completed our measurements in Lund, Sweden of the excitation functions of excited states in ionized carbon and nitrogen, following breakup of CN in a thin carbon foil. The results show the effect of a neighboring ion on the production of excited states is sensitive to the excitation energy. The measurements were made with very thin carbon foils and up to 6-MeV CN ion beams. The work will continue at Argonne in FY 1984 during a visit by Indrek Martinson.

---

*Department of Physics, University of Lund, Sweden.

d. Alignment and Orientation Production in Hydrogenic States (H. G. Berry, J. C. DeHaes,* D. Neek,† P. Somerville, and Y. Hui‡)

We have just begun a series of measurements to investigate the final surface interaction of a thin foil on a fast ion beam. It has become clear

---

*University of Brussels, Belgium.
†University of Illinois, Chicago, IL.
‡Fudan University, Shanghai, China.

from our and other people's previous investigations that the excitation distribution and wavefunction shapes depend on the bulk of the foil and, more critically, on the final surface interaction. Previous measurements on the existing particles have already allowed some preliminary analysis of the observed total charge-state distributions (see for example, Argonne reports by Berry and Brooks and also by Gemmell et al.). Our present objective is a more detailed microscopic understanding of the important final surface processes. These clearly include electron pick-up, excitation and stripping, and the effects of surface electric fields, both those induced by the moving ion (image fields etc.), and those produced by the secondary electron flux.

Our initial measurements have been made on the hydrogen Balmer series, and on the Fowler and Pickering series of the one-electron helium ion. First results obtained for the relative populations of different n-states showed that the light flux of the Balmer lines of hydrogen is proportional to n^{-8}. This implies a level population proportional to n^{-2}, as compared with the n^{-3} dependence predicted by a simple electron pick-up theory.

Initial polarization measurements of Balmer emission following the population of states with n=5 to 15, show an apparent strong increase in the alignment of high-n Rydberg states. These correspond closely to maximum orientation of the states around n=9. However, these high n-states are very sensitive to small electric fields. This sensitivity, due to strong mixing within the closely degenerate states causes them to be sensitive probes of the surface electric field. Thus, by measuring the "zero-field" quantum beats, we are able to obtain quantitative measurements of the surface field. We find that surface fields of up to 15 volts/cm exist out to a few mm from the foil surface. The true zero-field quantum beats start only after this field is small enough to minimize the mixing within the n-manifold being measured.

These measurements are continuing: we have already noted that the surface fields are sensitive to the beam flux (more secondary electrons), and to the foil resistance (a foil-thickness dependence). By tilting the foils we also observe the variation of the induced atomic orientation with the same parameters. The analysis of the data is complicated, but shows that earlier measurements of alignment in hydrogenic states were interpreted by too simple a set of models, all of which ignored these long-range surface fields.

e. Laser-Fast Ion Beam Interaction Beam-Line at the Dynamitron (H. G. Berry, W. J. Ray, B. J. Zabransky, and R. L. Amrein)

A new beam-line has been constructed in the Dynamitron target area especially for the study of the interactions of collinear ion and laser beams. The components of the beam line include two beam-deflection magnets downstream from the principal momentum-analysis magnet. These provide entrance and exit ports for the laser beam through Brewster-angle windows. Other components include a magnetic quadrupole lens, several removable quartz viewers, and three sets of four-jaw defining slits. A variety of interaction chambers allows selective neutralization and/or excitation of the ion beam, plus observation of laser-induced fluorescence. Several turbomolecular pumps produce a vacuum of about 5.10^{-7} Torr throughout the beamline.

f. Fast ion Beam - Laser Interactions (H. G. Berry, L. Young, J. E. Hardis,* P. Somerville and W. J. Ray)

We are using collinear laser excitation of fast ion beams to study a number of atomic structure problems. The problems include the determination of fine and hyperfine structure in light positive and negative ions, plus measurements of absolute wavelengths of light two-electron ions. In addition we intend to use a similar experimental arrangement to study excitation and decay of high Rydberg states first in the absence of fields and then in crossed electric and magnetic fields.

The general thesis behind the fast-beam laser experiments is to take advantage of the high velocity of the ions both to doppler shift a fixed single-frequency uv laser into resonance, and to reduce the natural doppler

*University of Chicago, Chicago, IL.

broadening in normal excited discharge cells. The interaction phase space of the laser and the ion beam is enhanced by the fact that the beams are collinear and are operated cw. All the above factors are necessary to make up for the small number of ions of a specific excited state of interest in the ion beam.

An initial experiment involves the study of the transition $1s2s2p^2\ {}^5P$ - $1s2p^3\ {}^5S$ in doubly-excited negative lithium. This transition is of considerable theoretical interest as it is the only electric dipole transition observed in a negative ion. Also, calculations show a strong mixing of the fine and hyperfine structure of the upper and lower levels of the transition (Hardis, Cheng and Beck, to be published). The major difficulty is the small fraction of excited states of Li^- produced in a lithium beam-gas collision system. Our first measurements indicate that we have less than 1 signal photon per second.

We are testing the experimental arrangement by excitation of Balmer-α in hydrogen, and by excitation of the $2p^5 3s\ {}^3P$ (J=2) metastable state in neutral neon. Observations of these resonances will enable us to calibrate the Dynamitron and Test Bench accelerator voltages to within a few volts - that is to a few parts in 10^5.

Two-photon doppler-free measurements in neon and sodium will give even more precise calibration of the accelerator voltages, and will be needed to obtain absolute wavelength measurements in other two-electron systems.

IX. INTERACTIONS OF FAST ATOMIC AND MOLECULAR IONS WITH SOLID AND GASEOUS TARGETS

Introduction

Argonne's 4.5-MV Dynamitron accelerator is used to study the interactions of fast (MeV) atomic and molecular ions with matter. A unique feature of the apparatus is the exceptionally high resolution (~0.005° and ~300 eV) in angle and energy obtained in detecting particles emerging from the target. The apparatus also permits the coincident detection of up to three molecular dissociation fragments. The work has as its main objective a general study of the interactions of fast charged particles with matter, but with the emphasis on those aspects that take advantage of the unique features inherent in employing molecular-ion beams (e.g., the feature that each molecular ion incident upon a solid target forms a tight cluster of atomic ions that remain correlated in space and time as they penetrate the target). In addition, we are able to study the structures of molecular ions that constitute the incident beams.

Tightly collimated beams of atomic molecular ions with energies variable in the range 0.5-4.5 MeV are directed onto thin (~100 Å) foil or gaseous targets. The distributions in energy and angle are measured with high resolution (~0.005 and ~300 eV) for the resultant ions. The major aim of the work is a general study of the interactions of fast ions with matter, but with emphasis on those aspects which take advantage of the use of molecular-ion projectiles. Specifically, the feature that each molecular ion incident upon a solid target forms a tight cluster of atomic ions that remain correlated in space and time both inside and outside the target provides a unique probe of atomic collision phenomena. This aspect has recently proved particularly powerful in the study of electron capture processes as fast ions exiting solids as well as in studying the role of high-Rydberg-state atoms in such processes. These experiments have been complemented by additional measurements of electron emission from foil-excited monatomic and molecular-ion beams.

In the course of developing techniques for determining the stereochemical structures of molecular projectiles by coincident detection of dissociation fragments, preliminary data have shown us the important problems which need to be addressed in order to obtain precise structural information. Most prominently, these problems include the need for a more detailed understanding of the physical processes involved in the interactions of these fast molecular ions with solid targets and the formation of final electronic states. This year, our efforts were primarily devoted to studying the charge-changing processes acting on fast ions as they exit from solid targets. We have studied the yields and quantum state populations of high-Rydberg-state atoms excited in fast heavy ion beams. These atoms were found to emerge with high probability when fast molecular-ion beams dissociate in foils. Our work was aimed at understanding the processes which lead to the formation of these atoms.

Also this year, we investigated the post-foil interaction of heavy molecular dissociation fragments. These data have helped shed new light on the processes which lead to the final charge-state distributions observed when fast ions emerge from solid targets. Some of the highlights in 1983 included:

a. Microwave Field Ionization of Fast Rydberg Atoms (P. Arcuni,* D. S. Gemmell, E. P. Kanter, P. M. Koch,† D. R. Mariani,† D. Schneider, W. van de Water,† and B. J. Zabransky)

In an attempt to determine the quantum-state populations for beam-foil excited high-Rydberg atoms, we collaborated with a group from Yale University in studying the microwave ionization of such atoms. We used a 9.91-GHz microwave cavity to ionize Rydberg atoms after production in a thin carbon foil, but before entering the electron spectrometer field used to energy-analyze the resulting electrons. Because of its high frequency, the variable microwave electric field had only a negligible effect on the energy spectrum of electrons originating prior to the cavity. By applying a bias voltage to the foil target, we were able to separate clearly those electrons produced at the target from those created in the cavity. An additional contribution was observed from field-ionization in the spectrometer field when the microwave field was reduced below the magnitude of that latter field.

This experimental geometry separates the ionizing field from the analyzing field, allowing us to vary the former to much higher values than we had been able to achieve before. With a microwave power of 18.4 watts, we achieved a maximum electric field of about 2.8 kV/cm which would ionize hydrogen atoms as low as n=24. Among the important findings of this work, we have demonstrated that these high-lying Rydberg states exhibit a $1/n^3$ quantum-state population after emerging from the foil (see Fig. IX-1). Analysis of the absolute yields obtained seems to indicate that the n-population is similar to the capture process for one-electron ions (see Table IX-1). It is hoped that a better understanding of the microwave ionization process will yield more detailed information about the distribution of kinetic energy of the electrons which we observe.

---

*Thesis student, University of Chicago, Chicago, Illinois.
†Yale University, New Haven, Connecticut.

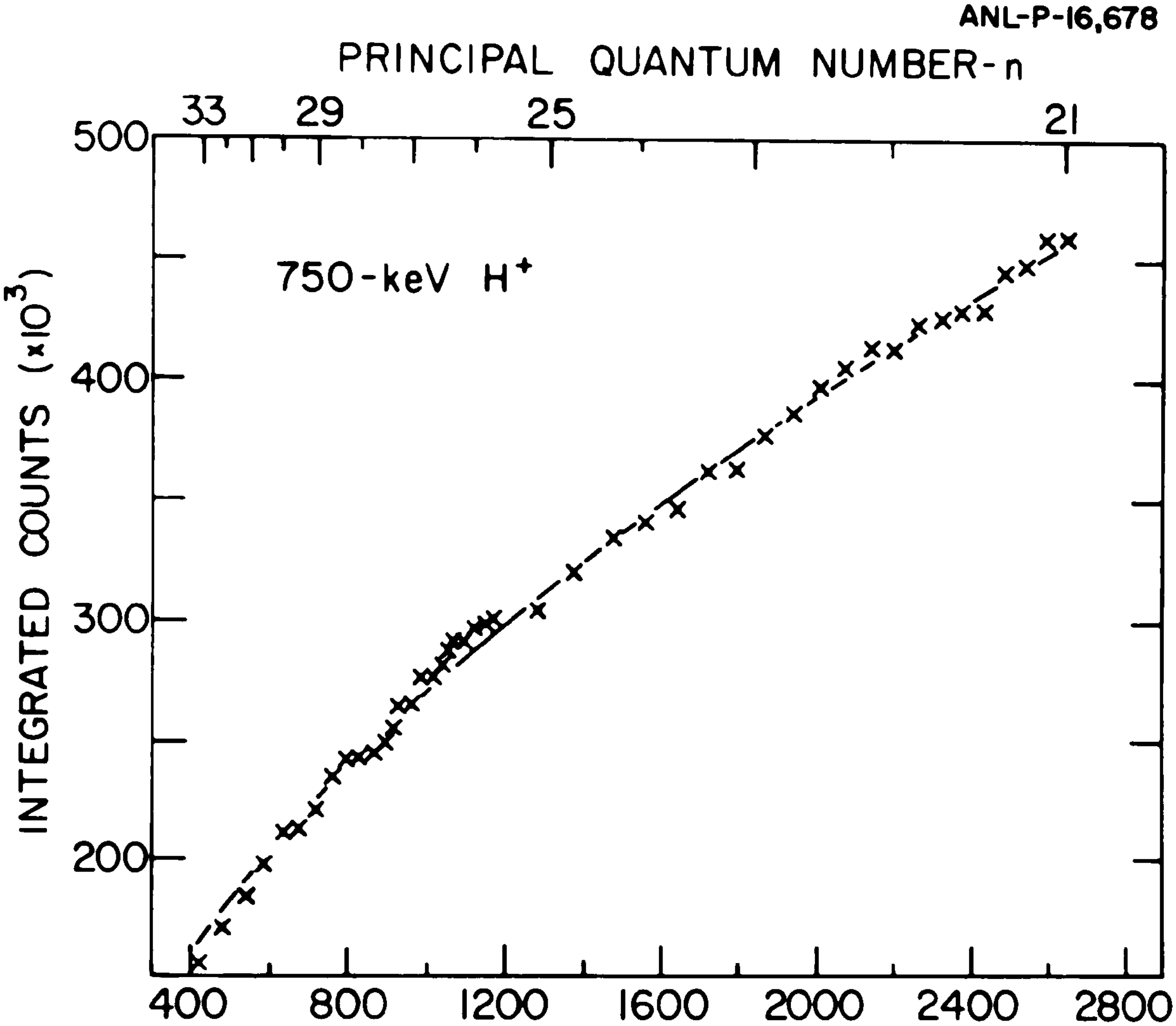

Figure IX-1. Integrated yield of the microwave-induced ionization peak observed in the 0° electron energy spectrum for 750-keV H^+ as a function of the maximum electric field in the microwave cavity. The upper abscissa represents the principal quantum numbers corresponding to the saddle-point threshold. The dashed line is the result of a fitting procedure assuming the quantum-state population to be $P(n) = a/n^{\gamma}$.

Table IX-1. Summary of analysis of microwave data.

Ion	Energy (MeV)	r	a	Single-electron yield	Convoy electron yield	ORNL Convoy electron yield
H^+	0.5	2.94±0.25	$2.3 \pm 0.6 \times 10^{-4}$	2.5×10^{-3}	2.0×10^{-7}	6.3×10^{-7}
H^+	0.75	3.33±0.29	$2.9 \pm 0.5 \times 10^{-4}$	1.1×10^{-3}	4.0×10^{-7}	3.7×10^{-7}
H^+	2.0	3.31±0.29	$1.7 \pm 0.5 \times 10^{-5}$	1.0×10^{-4}	7.4×10^{-8}	1.0×10^{-7}
He^+	2.0	3.00±0.25	$1.3 \pm 0.4 \times 10^{-2}$	6.3×10^{-2}	2.4×10^{-6}	4.2×10^{-6}
H_2^+	1.5	2.94±0.25	$5.6 \pm 1.7 \times 10^{-4}$	2.8×10^{-3}	3.3×10^{-7}	
		3.08±0.12				

b. Electric Field-ionization of Foil-excited Rydberg States of Fast Heavy Ions (D. S. Gemmell, E. P. Kanter, D. Schneider, and Z. Vager)

The absolute yield of beam-foil-excited Rydberg states was measured, using field-ionization techniques, for 125-MeV sulfur ions. This experiment, using fast ion beams obtained from the Argonne tandem-Linac accelerator, detected Rydberg states with principal quantum numbers in the range 250-650 (Fig. IX-2). The result was found to be consistent with a single-collision capture process in the last 16 Angstroms of the target, the depth corresponding to the mean free path for free-electron scattering of beam-velocity electrons. The yield which we have derived is a factor of 10-20 smaller than that given by cascade calculations used to explain the observed yields of delayed x-rays seen with such beams. These results point up the need to revise the assumed angular-momentum distributions assumed by such calculations. Additional work is underway to study the final-charge-state dependence of the high-Rydberg state yield of such fast heavy-ion beams.

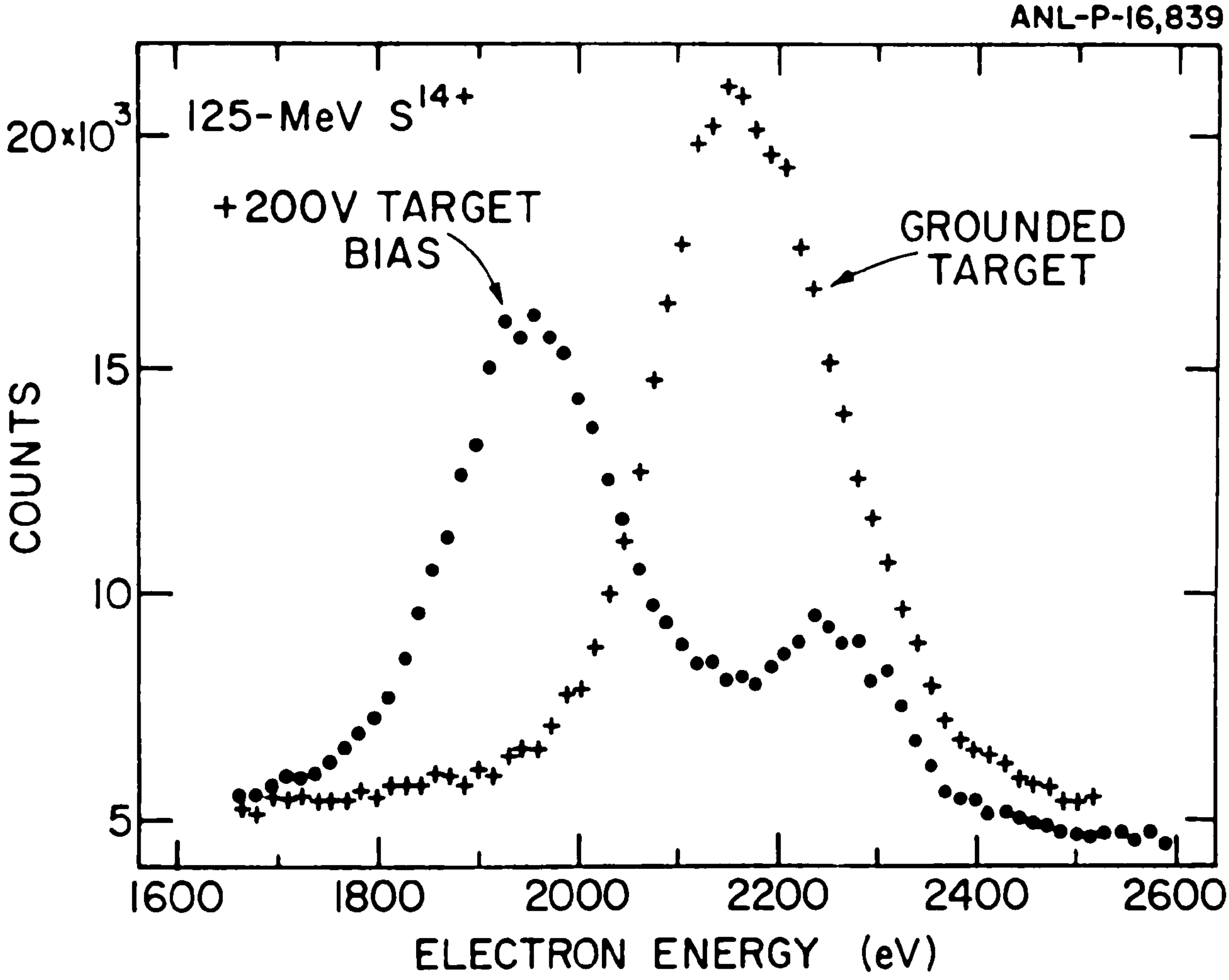

Figure IX-2. Electron energy spectra at 0° observation angle for 125-MeV S^{14+} ions incident upon a 5-μg/cm^2 carbon foil. The spectrum with +200 V bias on target reveals the presence of high Rydberg atoms which are field ioniozed in the spectrometer. The resulting electrons form the peak which does not shift with target bias.

c. The Post-foil Interaction in Foil-induced Molecular Dissociation (A. Faibis, E. P. Kanter, W. Koenig, I. Plesser, and Z. Vager)

We have investigated the foil-induced dissociation of 200- and 250-keV/amu CH^+, NH^+, and OH^+ ions by coincident detection of the fragment atoms resulting from the Coulomb explosion. By determining the relative flight times of the hydrogen and heavy-ion fragments to a set of detectors downstream of the target (Fig. IX-3), we were able to deduce the dissociation energies for the explosion in the foil, as well as for the post-foil interactions between the dissociation fragments. For final states consisting of bare protons accompanied by a heavy ion, the data show a marked deviation from a simple Coulomb interaction between point charges. We have succeeded in quantitatively fitting these data with a model which assumes an effective charge outside the foil depending on the internuclear separation of the dissociation fragments. Similarly, final states including neutral hydrogen fragments also show a surprising post-foil interaction dependent on the charge state of the accompanying partner dissociation fragment. The yields of such final states, including neutral hydrogen fragments, were found to be more highly favored compared to proton final states, when accompanied by higher charge-state partner ions.

We have also begun a study of the charge-state distributions of heavy-ion fragments resulting from the foil-induced dissociation of fast diatomic molecular ions. These data show a marked <u>decrease</u> in the resulting mean charge states when compared to those obtained with isotachic monatomic ion beams. The shift in the mean (typically 0.5-1.0 charge state) is also accompanied by a skewing of the charge-state distributions to lower charge states. We are attempting to explore this enhanced electron-capture phenomenon by measuring the dependence of these charge-state distributions on the relative separations of the exiting ions.

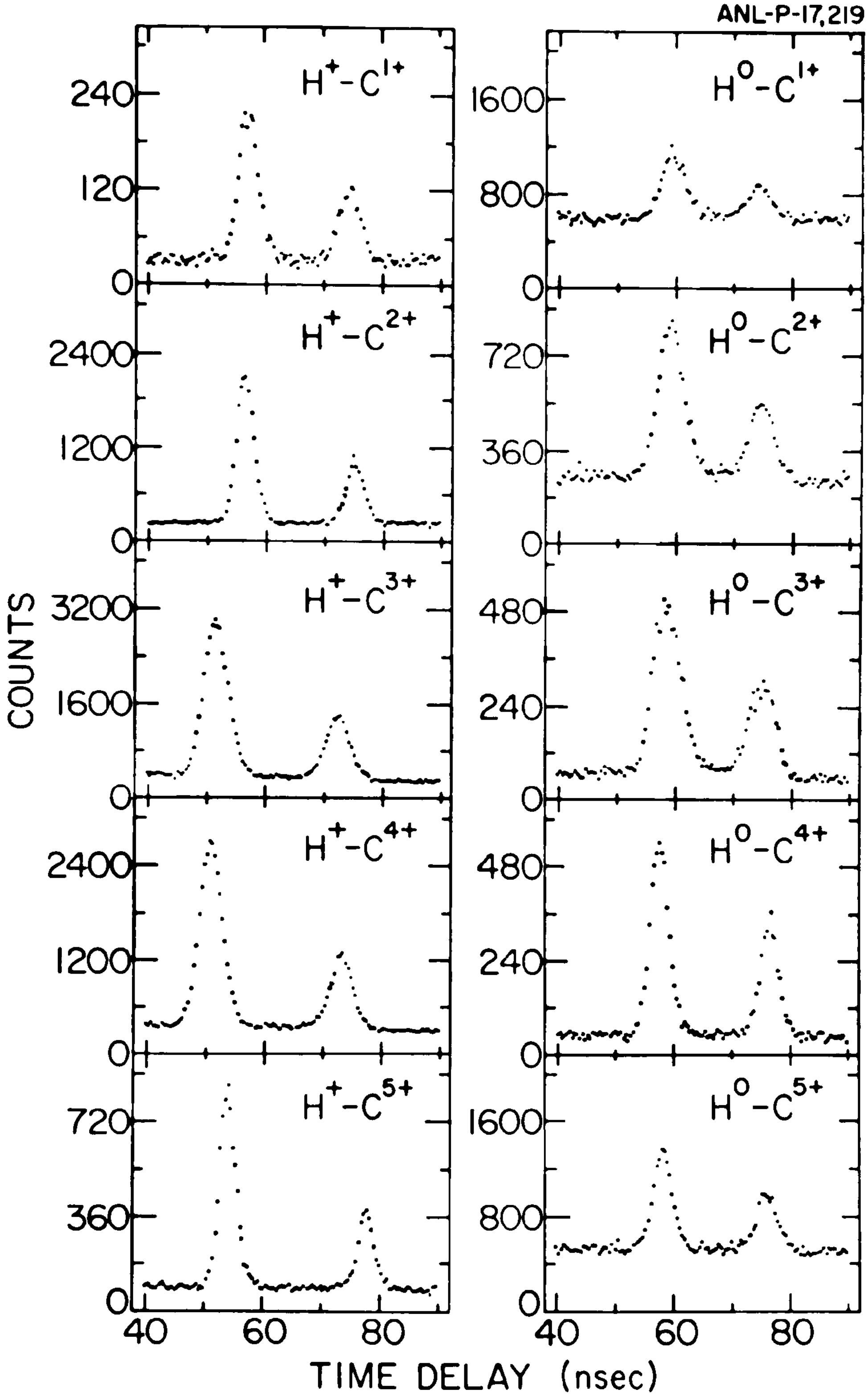

Figure IX-3. Time-delay spectra for various final states emerging from the foil-induced dissociation of 3.25-MeV CH^+.

d. Angular Distributions of Foil-excited Ions Bearing Inner Shell Vacancies (A. Faibis, J. Forster*, E. P. Kanter, W. Koenig, H. Kudo, and A. Minchinton)

Measurements on the angular distributions of fast ions traversing foils have shown a pronounced dependence of the multiple-scattering widths upon the charge state of the emerging ions (Fig. IX-4). We have successfully explained these results in terms of the large scattering angles achieved by those ions that bear K-vacancies. A quantitative model has been developed which demonstrates how the "memory" of K-vacancy producing collisions gives rise to large multiple-scattering widths in spite of apparent charge-state equilibration. An important result of this model is the prediction that He-like ions, which can be formed both with and without inner-shell vacancies, should exhibit both "normal" and anomalously large multiple-scattering widths dependent upon the presence of vacancies. We have succeeded in measuring the angular distributions of such ions in coincidence with KLL Auger electrons (for 3-MeV N^+ ions) and have demonstrated a wide hollow-center angular distribution for such ions, characteristic of the vacancy-producing collision in the foil, distinctly different from the normal distributions seen in singles. These measurements show promise for studying single collision phenomena in solid targets.

*Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

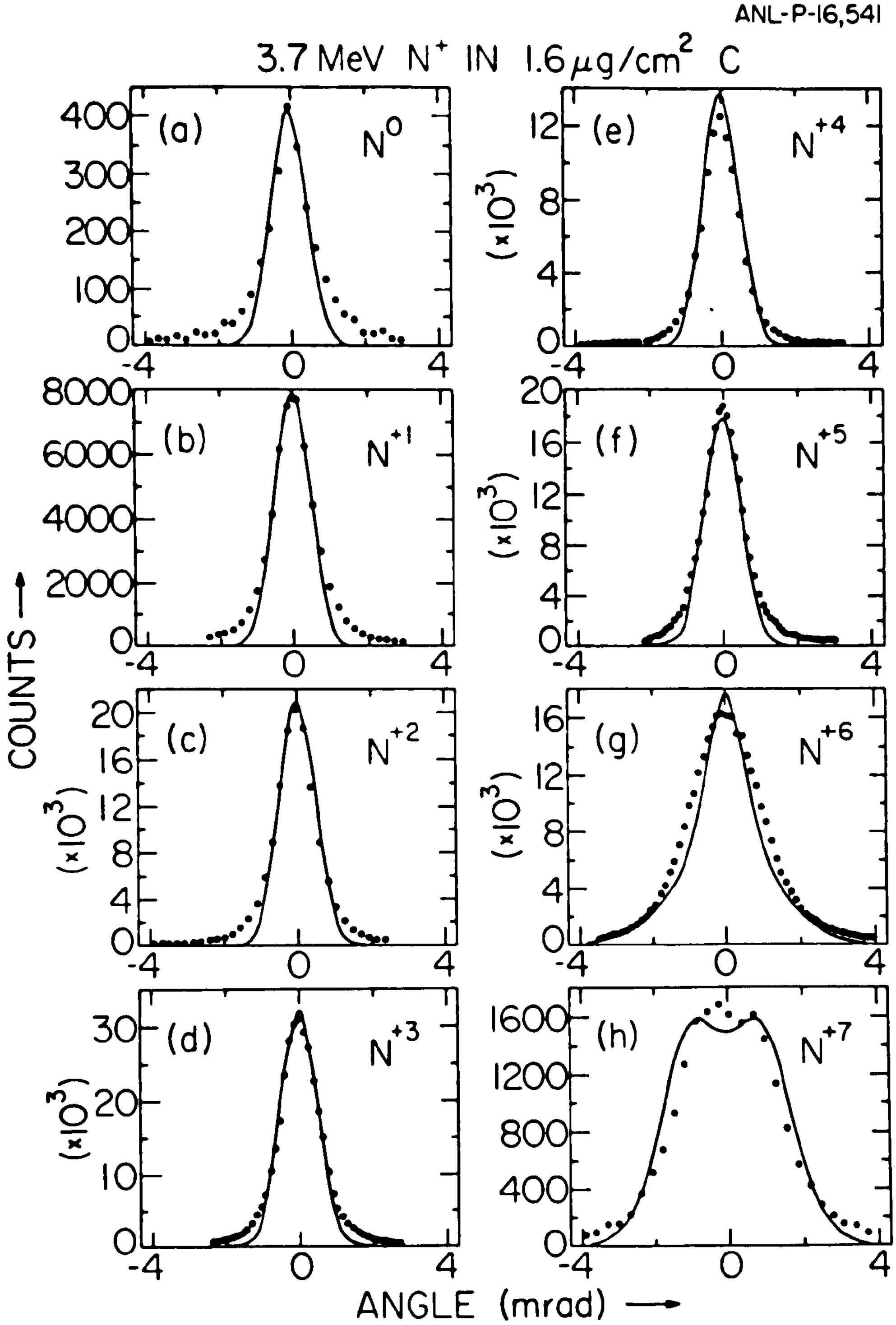

Figure IX-4. Measured angular distributions of nitrogen particles in all final charge states emerging from a 1.6-μg/cm^2 carbon target after impact of 3.7-MeV N^+ ions. Solid lines are calculated angular distributions, using the model described in text, corresponding to the experimental conditions of the data (filled points).

X. THEORETICAL ATOMIC PHYSICS

Introduction

This program is directed toward a detailed understanding of the role of relativity and electron correlation in atomic processes. The emphasis is on photoexcitation and photoionization where one can gain important insight into the dynamics of many-electron interaction in atoms and ions. Our current efforts include the systematic study of the ground-state hyperfine structures of rare earth elements using a technique based on the multiconfiguration Dirac-Fock method. The same technique is used to study the fine and hyperfine structures of the Li^- ion which are very sensitive to Breit interaction and electron-correlation effects. We are also studying the changes in the correlation effect along an isoelectronic sequence as reflected in the profiles of the autoionization resonances. Our purpose is to gain better understanding of the dynamics of Rydberg series interactions.

Our studies on relativistic many-body effects in atomic processes consist of four major parts, two of which involve bound-state energy levels and two of which deal with the autoionization and photoionization spectra.

(1) Hyperfine Structures of Rare Earth Elements. Atomic hyperfine structures (hfs) contain important information on the dynamics of relativity and electron correlations. We have developed an ab initio hfs theory based on the multiconfiguration Dirac-Fock (MCDF) technique. Preliminary results on the ground states of several rare earth atoms are in very good agreement with experiment. We are studying the systematics of the correlation effects on the hfs of the 4f shell. The chemical properties of the rare earths are determined mainly by the 4f orbital which goes through a sudden decrease in energy and size at the beginning of this group of elements. These hfs studies can provide important insights into the properties of the "collapsed" 4f orbital.

Values of nuclear quadrupole moments Q_I deduced from atomic hfs measurements are rather uncertain even though measurements of optical hyperfine splitting energies are very precise and reliable. This is because quadrupole shielding effect deforms the atomic core, which in turn affects the electronic valence states. However, nuclear quadrupole moments of rare earth elements as deduced from recent muonic hfs measurements are not affected by this problem because muonic orbials are essentially inside the atomic core. We are comparing the values of Q_I obtained from these muonic measurements with those from the usual electronic hfs experiments. This enables us to extract accurate values of the quadrupole shielding factors. Systematic behaviors of these factors in turn enable us to deduce accurate values of Q_I from electronic hfs data directly.

(2) Fine Structure of the $1s2s2p^2\ {}^5P$ State of the Negative Lithium Ion. We have calculated the fine and hyperfine structures of the ${}^5P$ state of

Li^- with the MCDF method. While the hyperfine structure is dominated by the contact interaction which can be calculated accurately, the fine structure is sensitive to Breit interaction and electron correlation which are more difficult to study theoretically. As the hyperfine spectrum of this quintet state is affected by the fine structure through second-order hyperfine interactions, it is important to obtain more accurate values of the fine structure splittings. We are carrying out a large scale configuration interaction calculation for the $1s2s2p^2\ ^5P$ and the $1s2p^3\ ^5S$ states of Li^-. To access the accuracy of our calculations, we shall make similar studies for the $1s2s2p\ ^4P$ and the $1s2p^2\ ^4P$ states of neutral Li where experimental data exist. These studies should provide important tests of relativistic correlation theories for atomic fine and hyperfine structures.

(3) Angular Distribution of the 5s Photoelectron of Xenon. Because of the spin-orbit interaction, the angular distribution asymmetry parameter β for the 5s photoelectron of Xe can deviate from its nonrelativistic value of 2 near the 5s cross section minimum. Our previous relativistic random-phase approximation (RRPA) calculations not only demonstrated this point but also showed that the energy dependence of β is very sensitive to final-state correlations as the weak $5s \rightarrow p$ channel is perturbed by the much stronger $5p \rightarrow d$ and $4d \rightarrow f$ channels. Recently, new measurements of this parameter in Xe show that in the region of the 5s cross section minimum, the deviation of β from its nonrelativistic value is actually not as large as that predicted by the RRPA. We are in the process of reexamining the final-state configuration interaction in the $5s \rightarrow \epsilon p$ photoionization of Xe. In particular, we would like to find out what is responsible for the residual discrepancy between the previous RRPA results and the new experimental data. The energy dependence of the β-parameter in the region of the cross section minimum is a very sensitive test of atomic correlation theory and these studies should provide insights into the dynamics of atomic photoionization processes.

(4) Systematic Trends in the Resonance Spectra of Closed-Shell Systems. The profiles of autoionization resonances contain important information on the dynamics of Rydberg series interactions. A recent study on the absorption spectra of Xe-like ions has shown rapid changes in the widths of the nd' resonances with increasing nuclear charge. While quantum defect analyses based on the Lu-Fano plots of the bound-state energy levels have confirmed the systematic trends of these resonance profiles, there is as yet no satisfactory explanation of the changing correlation effect along the isoelectronic sequence. We have developed a model to explain the systematic trends of the resonance profiles in terms of the enhancements of the correlation effect in the presence of a nearby shape resonance of the atomic central potential. Further tests of this model will be carried by studying the Beutler-Fano resonance spectra of Ne-, Ar-, and Kr-like ions with the relativistic random phase approximation.

a. Hyperfine Structures of Rare Earth Elements (K. T. Cheng)

Atomic hyperfine structures (hfs) are known to be sensitive to relativity and electron-correlation effects. Until recently, theoeretical hfs studies have been limited to light atoms where relativistic effects are not very important, and only semi-empirical techniques are available for heavy atoms. We have developed an ab initio theory based on the multiconfiguration Dirac-Fock (MCDF) method. As relativisitic effects are treated nonperturbatively, this theory is, in principle, applicable to any atomic systems. We have applied this technique to the hfs studies of the $4f^n6s^2$ ground states of rare earth elements. Results are in very good agreement with experiment. Further tests of this method are in progress.

b. Hyperfine Structure of the Quintet States of the Li^- Ion (K. T. Cheng and J. E. Hardis*)

The doubly-excited $1s2s2p^2\ {}^5P$ and $1s2p^3\ {}^5S$ states of Li^- are studied with the MCDF method. It is found that the fine and hyperfine structure of the ${}^5P$ state are of comparable magnitude. This leads to significant distortion of the Landé interval rule as states of the same quantum number F mix and repel. We discuss results of our MCDF and other calculations in this system, and also in the analogous lithium quartet systems where experimental data exist. We find that the hyperfine structures of these quintet and quartet states are dominated by the contact interaction, and that they are very insensitive to correlation effects. Experimental verification of the Li^- spectrum is underway at Argonne.

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

c. <u>4f Orbital Collapse for Pd-like and Cd-like Ions</u> (K. T. Cheng and C. Froese Fischer*)

Orbital collapse refers to the sudden decrease in energy and size of the 4f orbital in the rare earth region of the periodic table. It has profound influence on the spectra of these elements. Our recent study on the absorption spectra of Xe-like ions in the region of $4d \rightarrow nf$, ϵf excitations showed that orbital collapse is basically a shape-resonance effect arising from the interaction between the eigenstates of the inner potential well with those of the outer potential well. We have made similar studies on the absorption spectra of Pd-like and Cd-like ions with a combination of the term-dependent Hartree-Fock technique, the relativistic random-phase approximation, and the multichannel quantum-defect theory. The results clearly support our model of orbital collapse.

*Vanderbilt University, Nashville, Tennessee.

d. <u>Photoelectron Spectrum of Atomic Fluorine</u> (K. T. Cheng)

The spectrum of atomic fluorine in the region between the lowest ^3P and ^1D thresholds is studied with the MCDF method. Resonances that arise from the Rydberg series $2p^4(^1D)ns$, nd and $2p^4(^1S)ns$ are identified, and the associated oscillator strengths from the $2p^5\ ^2P$ ground state are calculated. Results on the resonance series that converge to the $2p^4\ ^1D$ threshold are in excellent agreement with experiment. The position of the $2p^4(^1S)3s$ line, however, is about 9 Å lower that the observed one at 680.7 Å (~ 1.4 %). Our results confirm the identification of the resonance lines in the observed spectrum.

e. <u>Absorption Spectrum of Ba^{++}</u> (K. T. Cheng)

The absorption spectrum of Ba^{++} in the region of $5p \rightarrow ns$, nd discrete excitations has been measured recently by Hill et al. at NBS. It shows large energy variations in the intensities of the absorption lines along Rydberg series that converge to the $^2P_{3/2}$ ionization limit. We employed the relativistic random-phase approximation (RRPA) to provide ab initio data for an eigen-channel analysis of this spectrum. We found that the variations in the intensities of the absorption lines are due to the interaction between the Rydberg series that converge to the $^2P_{3/2}$ threshold and those that converge to the $^2P_{1/2}$ one. Our finding is further supported by a quantum-defect analysis based on the Lu-Fano plot of the observed energy levels.

XI. ELECTRON SPECTROSCOPY WITH FAST ATOMIC AND MOLECULAR-ION BEAMS

Introduction

The 4.5-MV Dynamitron accelerator at Argonne has been used to carry out electron spectroscopy on excited ions produced as a result of the bombardment of gases and foils by fast (MeV) atomic and molecular-ion beams. This program complements other existing atomic physics research programs (e.g. beam-foil spectroscopy, interactions of fast molecular ions) in the Physics Division. Two different types of electrostatic electron spectrometers are available: a spherical analyzer and three parallel-plate analyzers (PPA). Electrons with energies up to about 20 keV can be analyzed. The spectrometers are incorporated in two new scattering chambers. The chamber which holds the PPA's is designed so that it can easily be modified and installed for use at different accelerators in the Physics Division. This chamber also permits easy variability of the analyzer observation angle. The spherical analyzer is used at a fixed angle (usually 90°). The energy resolution of the spectrometers can be tuned to less than 0.1% (FWHM).

One goal of the research is to investigate further the interactions of fast molecular ions with matter by studying details of the electronic states that are formed when ions exit foils in the proximity of partner fragments. Within these measurements we also investigate the formation of (atomic and molecular) Rydberg states in fast projectile ions. A new type of investigation in electron spectroscopy being planned involves fast ion-beam laser interactions. These studies are expected to provide more detailed insight into dynamic excitation processes. A further line of study involves the spectroscopy of Auger-electrons from solid targets excited by a variety of ion-species.

The study of inner-shell ionization phenomena arising in energetic ion-atom collisions has been a field of experimental and theoretical interest for many years. The experimental techniques of high-resolution electron and x-ray spectroscopy coupled with the availability of intense well-collimated, highly-monoenergetic beams of a great variety of atomic and molecular ionic species at MeV energies, have opened many new avenues of research into inner-shell ionization phenomena. Although most of the early experiments were performed under single-collision conditions (dilute gas targets), it has recently been demonstrated that a wealth of valuable additional information can be obtained when solid targets (thin foils) are employed. For studies involving low-Z atoms ($Z \lesssim 20$), the spectroscopy of Auger electrons is especially favored because of the low fluorescence yields.

The emission of Auger electrons following the dissociation of gas- and foil-excited fast (MeV) molecular-ion beams is investigated by measuring single-electron spectra with high resolution. The spectra from ionic fragments produced using molecular-ion beams are compared with spectra produced using monatomic ion beams of the same velocity.

High-resolution Auger electron spectroscopy on target and projectile species permits the study of excitation and transition probabilities for different projectiles. In the case of He, for example, autoionizing states have been shown to interfere with continuum states. The interference pattern, observed from the shapes of the lines observed in the electron spectrum, depends strongly on the electron observation angle and on the projectile velocity, and charge state. From angle-dependent high-resolution measurements it is possible to deduce the phase shift between the transition amplitudes for the resonant (autoionization) and non-resonant (direct ionization) processes. If, in addition to the ion-beam excitation, a laser is used for selective excitation for the "pumping" of excited states in the projectile or target atom, it should permit spectroscopy on "exotic" states that can only be produced in violent ion-atom collisions. The advent of intense tunable laser light sources has now made such experiments possible, e.g., the laser could prepopulate specific outer-shell target states which subsequently interact with a fast ion beam, producing inner-shell vacancies. This two-step excitation process may enhance the creation of those short-lived autoionizating and Auger states that are not efficiently formed in ion-atom collision processes without lasers.

a. Study of Li- and He-Autoionization as a Function of Projectile Velocity and Charge State (P. Arcuni,* H. Kudo,† D. Schneider, and W. Stöffler‡

The study of the helium autoionization spectrum will be continued as a function of Li-projectile charge state, the electron observation angle and the projectile velocity. The goal is to examine the interference between a resonant process (autoionization) and nonresonant process (direct ionization) both leading to the same final (ionic) state. This interference can be studied from an analysis of the asymmetric line profiles. By applying theoretical model calculations we can obtain the relative phase shift between the two relevant transition amplitudes as well as their relative magnitudes. The study thus provides a test of the theoretical descriptions.

---

*Graduate Student from the University of Chicago, Chicago, Illinois.
†Permanent address: University of Tsukuba, Japan.
‡Graduate Student from the Free University, Berlin, W. Germany

b. Auger Electron Measurements under Channeling Conditions for Projectile Ions (H. Kudo,* D. Schneider, E. P. Kanter, P. W. Arcuni,† and E. A. Johnson‡

The purpose of this study is to explore what kind of information on inner-shell excitation can be derived from the Auger-electron spectra under channeling conditions for projectile ions. Due to the atomic shadowing effect, the Auger-electron emission should be localized in the near-surface

---

*Permanent address: University of Tsukuba, Japan.
†Graduate Student from the University of Chicago, Chicago, Illinois.
‡Graduate Student from Oxford University, Oxford, England.

axis. This causes the characteristic deformation of the energy degradation spectra of Auger electrons. We observed such deformations for the case of Si K-Auger electrons, which were excited with 2.0-3.5-MeV H^+ under Si <110> and <111> channeling conditions (see Fig. XI-1). The Auger-electron yield ratio between the channeling and non-channeling cases was compared with the theoretical values, which were obtained with well-established Monte-Carlo simulations. The theoretical values depend on the assumed mean impact parameter b_m for Si K-shell ionization, so that we can determine b_m from the observed Auger yield ratio. However, the comparison between the observed and theoretical ratios shows the influence of angular multiple scattering suffered by the Auger electrons in Si. The correction for this effect in the analysis is needed when the observed electron energy is converted to the emission depth. This correction is anticipated to be about a 20-25% decrease in the estimated emission depth if b_m is assumed to be given by the semiclassical Coulomb approximation. We are analyzing this combined information on the Si K-shell ionization and the multiple scattering of Si K-Auger electrons (1.6 keV) in the Si near-surface region (depths less than ~100Å).

c. Laser-Stimulated Ar L-Shell Excitation in Slow Ion-Atom Collisions

We have studied Ar L-shell excitation in slow heavy ion-atom collisions for a large variety of collision systems. These studies have confirmed that inner-shell vacancy production in systems where the ion velocity is smaller than that of the relevant inner-shell orbital velocities can be understood as electron promotion via couplings between different molecular orbitals (MO's) formed during the collision process. We plan to perform experiments where we investigate the influence of L-shell vacancies in systems like N + Ar or Ar + Ar due to additional photon excitation and/or ionization of the quasimolecule formed in slow heavy ion-atom collisions.

ANL-P-17,413

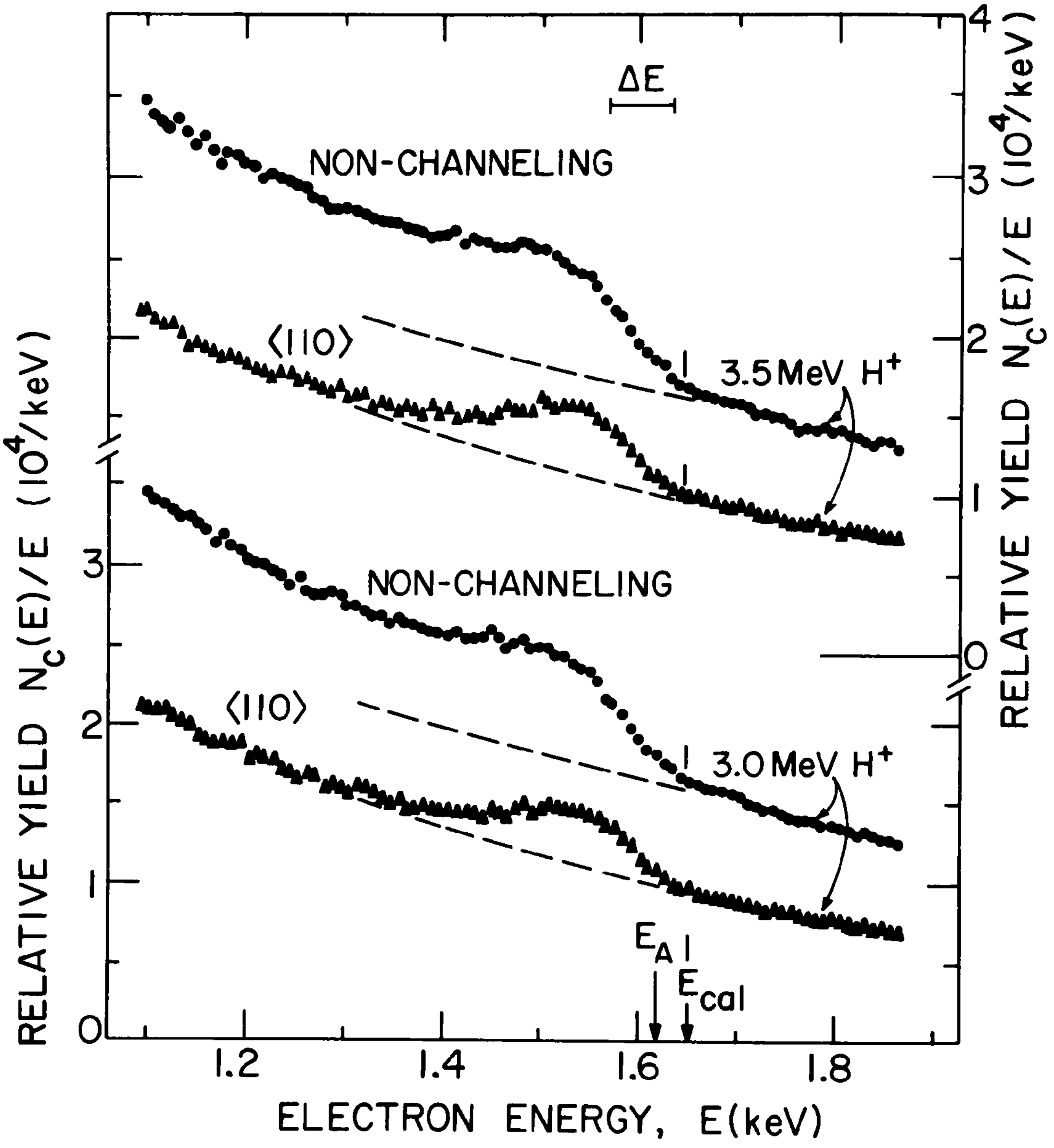

Fig. XI-1. Secondary-electron energy spectra for the Si<110> channeling an non-channeling cases of 3.5- and 3.0-MeV H^+, measured at a backward angle of 120° for the same number of H^+ incident perpendicularly on a Si single crystal. The dashed lines show the assumed baselines of the energy-degraded Si K-Auger electrons. E_{cal} is the calibration point of the energy axis. E_A(=1.62 keV) is the dominant emission energy of Si K-Auger electrons. Note that the relative yield of the electrons is given by $N_c(E)/E$ because the acceptance window of the electron spectrometer is effectively proportional to E. The spectrometer resolution, ΔE, is shown representatively for 1.6-keV electrons.

d. Simultaneous Laser- and Ion-Beam Excitation in Sodium

(D. Schneider, V. Pfeufer, W. Stoeffler,* H. G. Berry, L. P. Somerville, J. Hardis,† P. Arcuni,† R. Bruch,‡ P. Seidel,§ and C. F. Moore§)

We have studied the photoelectron spectra induced in a sodium vapor jet target by impact with fast helium ions of 1-MeV energy from the Dynamitron accelerator. High-resolution Auger electron spectra obtained with a spherical McPherson spectrometer allowed identification of many inner-shell excited states in Na^+ and neutral Na. We repeated the experiment with simultaneous excitation of the Na ground state by a single mode Ring dye laser tuned to the $3s^2S_{1/2}$-$3p^2P_{3/2}$ transition. Significant intensity variations of the Auger electron spectra were observed. A typical set of results is shown in Fig. XI-2. This laser-ion beam technique should help provide additional information on line identification and excitation mechanisms.

---

*Permanent address: Free University Berlin, Berlin, W. Germany.
†Graduate student from University of Chicago, Chicago, Illinois.
‡Permanent address: University of Freiburg, Freiburg, W. Germany.
§Permanent address: University of Texas, Austin, Texas.

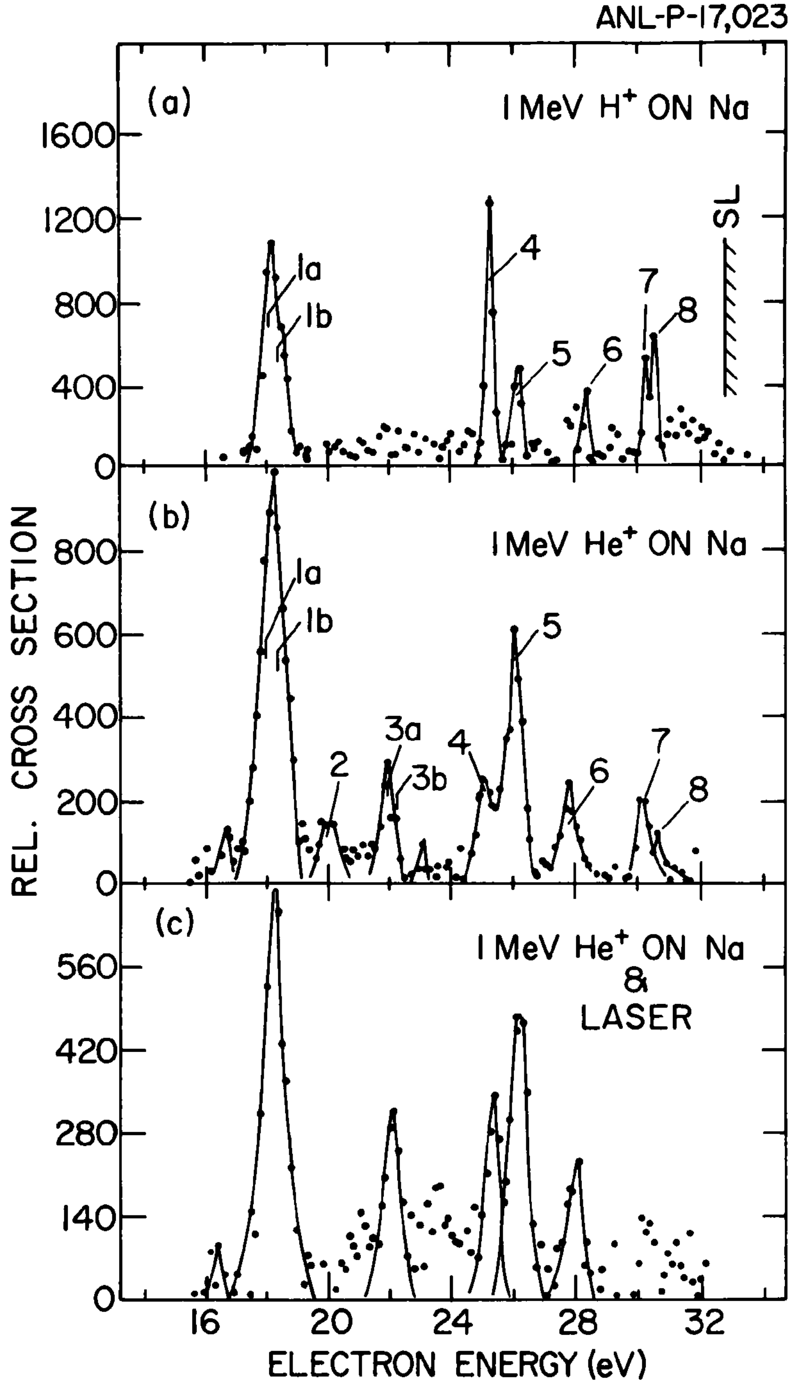

Fig. XI-2. Na L autoionization spectra for 1-MeV H^+ or He^+ on a sodium beam target. Observation is at 90° to the 2 beams with energy resolution of 100 MeV. Spectrum (c) shows the enhancement of some transitions following simultaneous laser excitation of the 3s $^2S_{1/2}$-^3P $^2P_{3/2}$.

STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the permanent staff of the Physics Division for the year ending 31 March 1984. The program heading indicates only the individual's current primary activity.

EXPERIMENTAL NUCLEAR PHYSICS AND ACCELERATOR PHYSICS

Scientific Staff

[*]Lowell M. Bollinger, Ph.D., Cornell University, 1951

Cary N. Davids, Ph.D., California Institute of Technology, 1967

[†]Melvin S. Freedman, Ph.D., University of Chicago, 1942

Stuart J. Freedman, Ph.D., University of California, 1972

[‡]Gerald T. Garvey, Ph.D., Yale University, 1962

Donald F. Geesaman, Ph.D., State University of New York, Stony Brook, 1976

Walter F. Henning, Ph.D., Technical University, Munich, 1968

Roy J. Holt, Ph.D., Yale University, 1972

Harold E. Jackson, Jr., Ph.D., Cornell University, 1959

Robert V. Janssens, Ph.D., Université Catholique de Louvain, Belgium, 1978

[§]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

Walter Kutschera, Ph.D., University of Graz, Austria, 1965

[†]Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937

[¶]James Napolitano, Ph.D., Stanford University, 1982

Richard C. Pardo, Ph.D., University of Texas, 1976

Karl Ernst Rehm, Ph.D., Technical University, Munich, 1973

---

[*]In charge of tandem-superconducting linac operations and the ATLAS project.

[†]Retired - research participant.

[‡]Joint appointment with the University of Chicago.

[§]Temporarily assigned to Max-Planck-Institut, Heidelberg, W. Germany (September 1983--March 1984).

[||]No longer in the Physics Division as of February 24, 1984.

[¶]Postdoctoral Appointee May 1982-November 1983. Regular staff December 1983.

[*]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

Lester C. Welch, Ph.D., University of Southern California, 1970

Jan L. Yntema, Ph.D., Free University of Amsterdam, 1952

Benjamin Zeidman, Ph.D., Washington University, 1957

DESIGN GROUP FOR MEDIUM/HIGH-ENERGY ACCELERATORS

Edwin A. Crosbie, Ph.D., University of Pittsburgh, 1952

Tat K. Khoe, Ph.D., Technische Hogeschool Delft, Netherlands, 1960

Robert L. Kustom, Ph.D., University of Wisconsin, 1969

THEORETICAL NUCLEAR PHYSICS

[‡]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

Tsung-Shung Harry Lee, Ph.D., University of Pittsburgh, 1973

[§]James E. Monahan, Ph.D., St. Louis University, 1951

[||]Murray Peshkin, Ph.D., Cornell University, 1951

Steven C. Pieper, Ph.D., University of Illinois, 1970

[¶]Robert B. Wiringa, Ph.D, University of Illinois, 1978

[†]Associate Director of the Physics Division. Joint appointment with the University of Chicago.

[‡]Joint appointment with the University of Illinois, Chicago Circle Campus.

[§]On disability status due to illness.

[||]Temporarily assigned to the Weizmann Institute of Science, Rehovoth, Israel (January 1984--May 1984).

[¶]Postdoctoral Appointee January 1981--July 1983. Regular staff August 1983.

ATOMIC AND MOLECULAR PHYSICS

Joseph Berkowitz, Ph.D., Harvard University, 1955

H. Gordon Berry, Ph.D., University of Wisconsin, 1967

Kwok-tsang Cheng, Ph.D., University of Notre Dame, 1977

William J. Childs, Ph.D., University of Michigan, 1956

*Donald S. Gemmell, Ph.D., Australian National University, 1960

Leonard S. Goodman, Ph.D., University of Chicago, 1952

Elliot P. Kanter, Ph.D., Rutgers University, 1977

Wolfgang Koenig, Ph.D., University of Marburg, 1979

†Gilbert J. Perlow, Ph.D., University of Chicago, 1940

‡Dieter Schneider, Ph.D., Free University of Berlin, 1945

§Zeev Vager, Ph.D. Weizmann Institute of Science, 1962

Linda Young, Ph.D., University of California, Berkeley, 1981

ADMINISTRATIVE STAFF

||Richard E. Combs, M.B.A., Lewis University, 1981

¶James R. Specht, A.A.S., DeVry Technical Institute, 1964

TEMPORARY APPOINTMENTS

Postdoctoral Appointees

Aurel Faibis (from Weizmann Institute of Science, Rehovoth, Israel): Structure of molecular ions and interactions of atoms with thin solid foils as revealed in fast ions - target collisions. (September 1983--   )

---

*Director of the Physics Division.

†Joint appointment as Editor of Applied Physics Letters.

‡No longer in the Physics Division as of June 1983. Present address: Hahn-Meitner Institute, Berlin, W. Germany.

§Joined the Physics Division Staff on part-time Sr. Scientist basis April 1984.

||Assistant Director of the Physics Division since September 1, 1983.

¶Assistant Director of the Physics Division.

William S. Freeman (from State University of New York, Stony Brook): Experimental heavy ion and charged particle nuclear physics. (December 1980--June 1983)

Michael Green (from Indiana University, Bloomington, Indiana): Optical pumping technique for producing polarized internal gas targets for ring accelerators. September 1983--)

William E. Kleppinger (from Stanford University, Stanford, California): Theory of electromagnetic and weak interactions in nuclear physics. (November 1982--)

Jayant Kumar (from the University of Minnesota, Minneapolis, Minnesota): Laser spectroscopy on radioactive atoms. (August 1983--)

Kevin T. Lesko (from the University of Washington, Seattle, Washington): Heavy ion nuclear physics. (June 1983--)

Alan Minchinton (from Flinders University, Adelaide, Australia): Collisional effects in the passage of fast molecular ions through thin foils and gases. (December 1982--August 1983)

*James J. Napolitano (from Stanford University, Stanford, California): Experimental studies of weak interactions and associated topics. (May 1982--November 1983)

Ronald S. Pandolfi (from University of California, Los Angeles, California): UV-laser photofragmentation of molecular ions. (December 1982--December 1983)

Volker H. Pfeufer (University of Hannover, Germany): RF laser spectroscopy on atoms, molecules, and ions. (July 1982--February 1984)

David C. Radford (from Yale University, New Haven, Connecticut): Research on high spin states and heavy-ion reactions. (February 1983--)

Branko M. Ruscic (from Rudjer Boskovic Institute, Zagreb, Yugoslavia): Photoionization and photoelectron spectroscopy. (September 1981--November 1983)

Lawrence P. Somerville (from Lawrence Berkeley Laboratory, Berkeley, California): Accelerator-based atomic physics: beam-foil spectroscopy; fast laser-ion beam interactions. (January 1983--)

George S. Stephans (from University of Pennsylvania, Philadelphia, Pennsylvania): Nuclear physics using heavy-ion beams from the ANL linac. (November 1982--)

---

*Assistant Physicist in the Physics Division as of December 1983.

Ernst Ungricht (from Eidgenossische Technische Hochschule, Zurich): Medium-energy pion scattering. (November 1982--)

*Robert B. Wiringa (from Los Alamos National Laboratory, Los Alamos, New Mexico): NN interaction, three-body forces, many-body theory for light nuclei, nuclear matter and neutron stars. (January 1981--July 1983)

Adriaan M. Van Den Berg (from the University of Groningen, The Netherlands): Experimental nuclear physics using heavy ions. (September 1983--)

Michael Vineyard (Florida State University, Tallahassee, Florida): Quasielastic neutron pickup reactions and incomplete fusion studies. (January 1984--)

<u>Long-Term Visitors</u> (at Argonne more than 4 months)

Ademola Amusa (University of Ife, Ile-Ife, Nigeria, Africa): Shell-model calculations in some nuclei (e.g., ^{20}O). (May 1983--October 1983)

†Dieter Frekers (University of Münster, Münster, West Germany): Experimental heavy-ion and charged-particle nuclear physics. (December 1981--November 1983)

‡Hiroshi Ikezoe (Japan Atomic Energy Research Institute, Tokai-Mura, Japan): Study of the nuclear reaction mechanism induced by the energetic heavy-ion beams. (October 1982--September 1983)

James J. Kolata (Notre Dame University, South Bend, Indiana): Research in heavy-ion reaction mechanisms at 8-10 MeV per nucleon. (July 1983--)

Hiroshi Kudo (University of Tsukuba, Japan): Accelerator-based atomic physics. (December 1982--March 1984)

Linwood L. Lee (State University of New York, Stony Brook, N.Y.): Studies of heavy-ion reaction mechanisms. (January 1984--)

Olivera Neskovic (Boris Kidric Institute, University of Belgrade, Yugoslavia): Photoelectron-photoionization spectroscopy. (November 1983---)

---

*Assistant Physicist in the Physics Division as of July 1983.

†Deutsche Forschungsgemeinschaft Fellowship.

‡U.S.--Japan Collaboration for Nuclear Physics.

*Günther U. H. Rosner (Max-Planck-Institut für Kernphysik, Heidelberg, Germany): Heavy-ion physics; reaction mechanisms; fusion and heavy-ion reactions; charged-particle observation; γ-ray deexcitation. (June 1982--December 1983)

Songlan Sun (Institute of High Energy Physics, Beijing, Peoples Republic of China): Conceptual design of recirculating injector for BEPC. (April 1983--October 1983)

†Suehiro Takeuchi (Japan Atomic Energy Research Institute, Tokai-Mura, Japan): Investigation of superconducting linac technology. (October 1982--March 1984)

Resident Graduate Students

Philip W. Arcuni (University of Chicago, Chicago, Illinois): Electron spectroscopy of ion-atom collisions. (October 1981--   )

Jordan B. Camp (University of Chicago, Chicago, Illinois): Weak interactions. (October 1982--   )

Rollin M. Evans (Iowa State University, Ames, Iowa): On-line laser spectroscopy of radioactive atoms using the superconducting linac. (March 1981--August 1983)

Miles A. Finn (University of Minnesota, Minneapolis, Minnesota): On-line laser spectroscopy of radioactive atoms using the superconducting linac. (April 1981--   )

Jonathan E. Hardis (University of Chicago, Chicago, Illinois): Ion-ion and ion-atom collisions. (October 1979--January 1984)

Alexandra R. Heath (University of Chicago, Chicago, Illinois): Weak interactions in nuclear physics. (January 1979--May 1983)

Michael A. Kroupa (University of Chicago, Chicago, Illinois): Search for magnetic monopoles using a plastic scintillator array. (July 1982--   )

Wolfram Stöffler (Freie Universität, Berlin, Germany): Electron spectroscopy with laser and fast ion-beam interaction. (July 1982--July 1983)

Frank L. H. Wolfs (University of Chicago, Chicago, Illinois): Research in heavy-ion physics. (September 1983--   )

---

*Alexander von Humboldt Foundation Fellow.

*U.S.--Japan Collaboration for Nuclear Physics.

Short-Term Visitors (at Argonne less than 4 months)

A. Faculty

Isaac D. Abella (University of Chicago, Chicago, Illinois): Laser interactions with fast particle beams (June 1983--August 1983)

Daniel Ashery (Tel Aviv University, Tel Aviv, Israel): Study of pion absorption in ^{3}He. (July 1983--October 1983)

Patrick J. Cooney (Millersville State College, Millersville, Pennsylvania): Studies of the interaction of fast-moving ions with matter. (May 1983--August 1983)

Alejandro Szanto de Toledo (University of Sao Paulo, Brazil): Heavy-ion physics research. (September--October 1983)

Alan K. Edwards (University of Georgia, Athens, Georgia): Laser dissociation of molecular ions. (August 1983--September 1983)

Dusan Krajcinovic (University of Illinois, Chicago Circle, Chicago, Illinois): Study of neutrino oscillations. (July 1983--August 1983)

David A. Lewis (Iowa State University, Ames, Iowa): On-line laser spectroscopy of radioactive atoms using the superconducting linac. (August 1983--December 1983)

*Harry J. Lipkin (Weizmann Institute of Science, Rehovot, Israel): Angular momentum in electromagnetic fields of solenoids and monopoles; applications of the constituent quark model to hadron spectroscopy. (June 1983--October 1983)

Malcolm H. Macfarlane (Indiana University, Bloomington, Indiana): Theoretical nuclear physics. (May 1983)

Itzhak Plesser (Weizmann Institute of Science, Rehovoth, Israel): Accelerator-based atomic and molecular physics. (August 1983--September 1983)

Eloisa Szanto (University of Sao Paulo, Brazil): Heavy-ion physics research. (September--October 1983)

Wayne N. Polyzou (University of Iowa, Iowa City, Iowa): Formalism for relativistic scattering theory of directly interacting quarks. (June 1983--August 1983)

Ralph E. Segel (Northwestern University, Evanston, Illinois): Pion absorption, inclusive reactions, low-energy capture. (August 1983--September 1983)

*Joint appointment with Argonne High Energy Physics Division and with Fermi National Accelerator Laboratory, Batavia, Illinois.

Qamar N. Usmani (Aligarh University, Aligarh, India): Theoretical research in hypernuclear physics. (June 1983--August 1983)

Zeev Vager (Weizmann Institute of Science, Rehovot, Israel): Coulomb explosion research. (August 1983--September 1983)

Hui Ye (Fudan University, Peoples Republic of China): Studies in beam foil spectroscopy. (June 1983--August 1983)

Dino Zei (Ripon College, Ripon, Wisconsin): Studies in beam foil spectroscopy. (May 1983--August 1983)

B. Graduate Students

*Irene Dorion (Institute of Nuclear Sciences, Grenoble, France): Response test of a "Breskin" detector. (June 1983--October 1983)

Edward A. Johnson (Oxford University, Oxford, England): Studies in electron and proton channeling. (July 1983--September 1983)

Ulrik Leif Nielsen (University of Aarhus, Aarhus, Denmark): Laser spectroscopy of molecular and atomic beams. (May 1983--December 1983)

C. Undergraduate Students

Joseph Bittman (Illinois Institute of Technology, Chicago, Illinois). (January 1984--)

Steven Cerny (University of Illinois, Urbana, Illinois). (May 1983--August 1983)

Todd A. Drumm (Westminster College, New Wilmington, Pennsylvania). (January 1983--April 1983)

Christopher Merrill (Illinois Institute of Technology, Chicago, Illinois). (January 1984--)

John J. Stewart (Lewis University, Lockport, Illinois). (August 1983--)

Tracey Tullos (Sam Houston State College, Huntsville, Texas). (January 1984--)

Kenneth J. Wasniewski (Lewis University, Lockport, Illinois). (September 1983--)

Ann Williamson (Tulane University, New Orleans, Louisianna). (January 1984--)

David B. Young (Hope College, Holland, Michigan). (January 1983--August 1983)

---

*American Nuclear Society Exchange Student.

TECHNICAL AND ENGINEERING STAFF

Ralph Benaroya

Peter J. Billquist

John M. Bogaty

*Patric K. Den Hartog

William F. Evans

Joseph Falout

John P. Greene

Raymond B. Kickert

Gary Klimczak

Robert Kowalczyk

Bruce G. Nardi

James E. Nelson

Robert W. Nielsen

Walter Ray, Jr.

James N. Worthington

†Jerome R. Wrobel

‡Bruce J. Zabransky

Gary P. Zinkann

---

*In charge of Tandem accelerator operations.

†No longer in the Physics Division as of February 2, 1984.

‡In charge of Dynamitron accelerator operations.

PUBLICATIONS FROM 1 APRIL 1983 THROUGH 31 MARCH 1984

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. JOURNAL ARTICLES AND BOOK CHAPTERS

Inclusive Pion Scattering in the Δ(1232) Region
S. M. Levenson, D. F. Geesaman, E. P. Colton, R. J. Holt, H. E. Jackson, J. P. Schiffer, J. R. Specht, K. E. Stephenson, B. Zeidman, R. E. Segel, P. A. M. Gram, and C. A. Goulding
Phys. Rev. C 28, 326 (1983)

Inelastic Scattering of 162-MeV Pions by ^{14}N
D. F. Geesaman, D. Kurath, G. C. Morrison, C. Olmer, B. Zeidman, R. E. Anderson, R. L. Boudrie, H. A. Thiessen, G. S. Blanpied, G. R. Burleson, R. E. Segel, and L. W. Swenson
Phys. Rev. C 27, 1134 (1983)

Meson-Exchange Currents and the Reaction $^{2}H(\gamma,n_{pol})H$
R. J. Holt, K. Stephenson, and J. R. Specht
Phys. Rev. Lett. 50, 577 (1983)

Tensor Polarization in π-d Scattering and Pion Absorption
E. Ungricht, W. S. Freeman, D. F. Geesaman, R. J. Holt, J. R. Specht, B. Zeidman, E. J. Stephenson, J. D. Moses, M. Farkhondeh, S. Gilad, and R. P. Redwine
Phys. Rev. Lett. 52, 333 (1984)

Measurement of the Tensor Polarization in Electron-Deuteron Elastic Scattering
M. E. Schulze, D. Beck, M. Farkhondeh, S. Gilad, R. Goloskie, R. J. Holt, S. Kowalski, R. M. Laszewski, M. J. Leitch, J. D. Moses, R. P. Redwine, D. P. Saylor, J. R. Specht, E. J. Stephenson, K. Stephenson, W. Turchinetz, and B. Zeidman
Phys. Rev. Lett. 52, 597 (1984)

$^{16}O(0^-)$ Beta Decay and Weak Axial Vector Meson Exchange Currents
C. A. Gagliardi, G. T. Garvey, J. R. Wrobel, and S. J. Freedman
Phys. Rev. C 28, 2423 (1983)

$0^+ \to 0^-$ Beta Decay of ^{16}O
C. A. Gagliardi and G. T. Garvey
Phys. Rev. C 27, 1353 (1983)

A Liquid Scintillator Cosmic Ray Active Shield
Stuart J. Freedman, Gerald T. Garvey, Michael Kroupa, James Napolitano, and James Worthington
Nucl. Instrum. Methods 215, 71 (1983)

Cryogenic Search for Fractionally Charged Particles
W. Kutschera, J. P. Schiffer, D. Frekers, W. Henning, M. Paul, K. W. Shepard, C. D. Curtis, and C. W. Schmidt
Phys. Rev. D 29, 791 (1984)

Search for a Light Scalar Boson Emitted in Nuclear Decay
S. J. Freedman, J. Napolitano, J. Camp, and M. Kroupa
Phys. Rev. Lett. 52, 240 (1984)

Possibility of Observing Recoilless Resonant Neutrino Absorption
William P. Kells and John P. Schiffer
Phys. Rev. C 28, 2162 (1983)

Power Electronics II
Robert L. Kustom
Fundamental Handbook of Electrical and Computer Engineering, Vol. I "Circuits, Fields, and Electronics," ed. Sheldon S. L. Chang (John Wiley & Sons 1983), p. 465

Large Cross Sections for Quasielastic Neutron-Pickup Reactions Induced by ^{37}Cl, ^{48}Ti, and ^{58}Ni on ^{208}Pb
K. E. Rehm, D. G. Kovar, W. Kutschera, M. Paul, G. Stephans, and J. L. Yntema
Phys. Rev. Lett. 51, 1426 (1983)

^{12}C on ^{48}Ca Transfer Reactions: A Test of the Effective Q-value Model
J. F. Peterson, R. J. Ascuitto, D. G. Kovar, W. Henning, and S. J. Sanders
Phys. Rev. C 28, 710 (1983)

Neutron-Excess Dependence of Fusion--Ni + Sn
W. S. Freeman, H. Ernst, D. F. Geesaman, W. Henning, T. J. Humanic, W. Kühn, G. Rosner, J. P. Schiffer, B. Zeidman, and F. W. Prosser
Phys. Rev. Lett. 50, 1563 (1983)

Evaporation Residue Cross Sections for ^{32}S + $^{112,116,120,124}Sn$ from X-ray and Direct Recoil-Nucleus Measurements
H. Ernst, W. Henning, C. N. Davids, W. S. Freeman, T. J. Humanic, F. W. Prosser, and R. A. Racca
Phys. Rev. C 29, 464 (1984)

Atomic Charge States of Residual Nuclei from Compound Nucleus Reactions
W. S. Freeman, H. Ernst, D. F. Geesaman, W. Henning, T. J. Humanic, W. Kühn, J. P. Schiffer, B. Zeidman, and F. W. Prosser
Phys. Rev. C 28, 919 (1983)

Suppression of Neutron Emission after Heavy-Ion Fusion: Is Shape Relaxation Affected by a Superdeformed Minimum?
W. Kühn, P. Chowdhury, R. V. F. Janssens, T. L. Khoo, F. Haas, J. Kasagi,and R. M. Ronningen
Phys. Rev. Lett. 51, 1858 (1983)

Nucleon Alignment to Very High Spins in ^{147}Gd: Rapid "Rotation" of a Fermion System
G. Sletten, S. Bjornholm, J. Borggreen, J. Pedersen, P. Chowdhury, H. Emling, D. Frekers, R. V. F. Janssens, T. L. Khoo, Y. H. Chung, and M. Kortelahti
Phys. Lett. B 135, 33 (1984)

Aligned $\nu i_{13/2}$ Bands Coupled to Different Shapes in ^{186}Hg
R. V. F. Janssens, P. Chowdhury, H. Emling, D. Frekers, T. L. Khoo, W. Kühn, Y. H. Chung, P. J. Daly, Z. W. Grabowski, M. Kortelahti, S. Frauendorf, and J. Y. Zhang
Phys. Lett. 131B, 35 (1983)

Nuclear Shape Transitions and Some Properties of Aligned-Particle Configurations at High Spin
T. L. Khoo, P. Chowdhury, H. Emling, D. Frekers, R. V. F. Janssens, W. Kühn, A. Pakkanen, Y. H. Chung, P. J. Daly, Z. W. Grabowski, H. Helppi, M. Kortelahti, S. Bjornholm, J. Borggreen, J. Pedersen, and G. Sletten
Physica Scripta T5, 16 (1983)

Level Structure of ^{153}Dy and the Competition Between Collective and Few-Particle Excitation Modes in Dy Nuclei
M. Kortelahti, R. Broda, Y. H. Chung, P. J. Daly, H. Helppi, J. McNeill, A. Pakkanen, P. Chowdhury, R. V. F. Janssens, T. L. Khoo, and W. Kühn
Phys. Lett. 131B, 305 (1983)

$(\pi h_{11/2}\ \nu h_{11/2}^{-1})$ 10^+ Isomers in N = 81 Nuclei ^{146}Tb, ^{148}Ho, and ^{150}Tm
R. Broda, Y. H. Chung, P. J. Daly, Z. W. Grabowski, J. McNeill, R. V. F. Janssens, and D. C. Radford
Z. Phys. A - Atoms and Nuclei 316, 125 (1984)

Half-life of ^{44}Ti
D. Frekers, W. Henning, W. Kutschera, K. E. Rehm, R. K. Smither, J. L. Yntema, R. Santo, B. Stievano, and N. Trautmann
Phys. Rev. C 28, 1756 (1983)

Levels in ^{38}K from the ^{40}Ca(d,α) Reaction at 22.8 MeV
C. M. Bhat, N. G. Puttaswamy, H. T. Fortune, and J. L. Yntema
Phys. Rev. C 28, 141 (1983)

Study of the ^{39,41}K(d,^{3}He)^{38,40}Ar Reactions at 22.8 MeV
C. M. Bhat, M. Rajo Rao, N. G. Puttaswamy, and J. L. Yntema
Nucl. Phys. A394, 109 (1983)

Branching Ratio in the Electron-Capture Decay of ^{7}Be
C. N. Davids, A. J. Elwyn, B. W. Filippone, S. B. Kaufman, K. E. Rehm, and J. P. Schiffer
Phys. Rev. C 28, 885 (1983)

Proton Capture Cross Section of ^{7}Be and the Flux of High Energy Solar Neutrinos
B. W. Filippone, A. J. Elwyn, C. N. Davids, and D. D. Koetke
Phys. Rev. C 28, 2222 (1983)

Level Structure of ^{67}Ge and its Implications for the General Structure of Nuclei in the 1f-2p Shell
Martin J. Murphy and Cary N. Davids
Phys. Rev. C 28, 1069 (1983)

Nuclear Saturation and Nuclear Forces
B. D. Day
Comments on Nucl. Part. Phys. 11, 115 (1983)

Many-Body Forces in Directly Interacting Systems
T. Biswas, F. Rohrlich, and M. King
Il Nuovo Cimento 77, 49 (1983)

Effective Operators in the Relativistic Meson-Nucleon System
H. Kümmel
Phys. Rev. C 27, 765 (1983)

Quenching of Stretched Magnetic Transitions
A. Amusa and R. D. Lawson
Phys. Rev. Lett. 51, 103 (1983)

The Effect of the Δ(1236) on the g-Factor of Nucleons
R. D. Lawson
Phys. Lett. 125B, 255 (1983)

Meson-Exchange Hamiltonian for NN Scattering up to 1 GeV and Δ-Nucleus Dynamics
T.-S. H. Lee
Phys. Rev. Lett. 50, 1571 (1983)

Meson theory of Nucleon-Nucleon Scattering up to 2 GeV
T.-S.H. Lee
Phys. Rev. C 29, 195 (1984)

Static-Bag-Source Meson Field Theory: Strong Coupling Approximation
John A. Parmentola
Phys. Rev. D 27, 2686 (1983)

Calculations of Ground-State Properties of Liquid ^{4}He Droplets
V. R. Pandharipande, J. G. Zabolitzky, S. C. Pieper, R. B. Wiringa, and U. Helmbrecht
Phys. Rev. Lett. 50, 1676 (1983)

Binding Energies of Hypernuclei and Three-Body ΛNN Forces
A. R. Bodmer, Q. N. Usmani and J. Carlson
Phys. Rev. C 29, 684 (1984)

Calculations of Pion Excess in Nuclei
B. L. Friman, V. R. Pandharipande, and R. B. Wiringa
Phys. Rev. Lett. 51, 763 (1983)

Three-nucleon Interaction in 3-, 4- and ∞-body Systems
J. Carlson, V. R. Pandharipande, and R. B. Wiringa
Nucl. Phys. A401, 59 (1983)

Interplay Between Two- and Three-Body Interaction in Light Nuclei and Nuclear Matter
Robert B. Wiringa
Nucl. Phys. A401, 86 (1983)

Pion Density in Nuclei and Deep Inelastic Lepton Scattering
E. L. Berger, F. Coester, and R. B. Wiringa
Phys. Rev. D 29, 398 (1984)

Effects of Magnetic Monopoles on Nuclear Wave Functions and Possible Catalysis of Nuclear Beta Decay and Spontaneous Fission
Harry J. Lipkin
Physics Letters 133B, 347 (1983)

High Spin States in ^{91}Tc
A. Amusa and R. D. Lawson
Z. Phys. A 314, 205 (1983)

Microcomputer Control of a Current Source DC-DC Converter
Mehrdad Ehsani, Robert L. Kustom, and R. E. Fuja
IEEE Trans. on Industry App. IA-19, 690 (1983)

Photoelectron Spectra of the Lanthanide Trihalides and Their Interpretation
B. Ruscic, G. L. Goodman, and J. Berkowitz
J. Chem. Phys. 78, 5443 (1983)

Photoionization of Atomic Chlorine
B. Ruscic and J. Berkowitz
Phys. Rev. Lett. 50, 675 (1983)

Photoionisation of Atomic Fluorine
B. Ruscic, J. P. Greene, and J. Berkowitz
J. Phys. B: At. Mol. Phys. 17, L79 (1984)

Crossed-Second-Order Effects in the Isotope Shift of the Ground Configuration $4f^{12}6s^2$ of Er I
V. Pfeufer, W. J. Childs, and L. S. Goodman
J. Phys. B: At. Mol. Phys. 16, L557 (1983)

Hyperfine Structure of the $4f^{12}6s^{2}\,{}^3H$ and ^3F Terms of ^{167}Er I by Atomic-beam Laser-rf Double Resonance
W. J. Childs, L. S. Goodman, and V. Pfeufer
Phys. Rev. A 28, 3402 (1983)

Hyperfine Structure of Low-Lying Even Levels of $^{161,163}Dy$ and ^{167}Er by Atomic-Beam Laser-rf Double Resonance
W. J. Childs, L. S. Goodman, and V. Pfeufer
Z. Phys. A. - Atoms and Nuclei 311, 251 (1983)

The Hyperfine Structure of Alkaline-Earth Monohalide Radicals: New Methods and New Results 1980-1982
W. J. Childs
Comments At. Mol. Phys. 13, 37 (1983)

Hyperfine Structure of $4f^N$ $6s^2$ Configurations in ^{159}Tb, $^{161,163}Dy$, and ^{169}Tm
W. J. Childs, H. Crosswhite, L. S. Goodman, and V. Pfeufer
J. Opt. Soc. B 1, 22 (1984)

Electric-Dipole Moment of $CaF(X^2\Sigma^+)$ by Molecular Beam, Laser-rf, Double-resonance Study of Stark Splittings
W. J. Childs, L. S. Goodman, U. Nielsen, and V. Pfeufer
J. Chem. Phys. 80, 2283 (1984)

J. Dependence of the Isotope Shift in the Ground Term of Dysprosium I
V. Pfeufer, W. J. Childs, and L. S. Goodman
J. Opt. Soc. Am. B, 1, 34 (1984)

Multi-Charged Ion Spectroscopy
H. G. Berry
Physica Scripta. T3, 56 (1983)

Collapse of the 4f Orbital for Xe-like Ions
K. T. Cheng and C. Froese Fischer
Phys. Rev. A 28, 2811 (1983)

Orbital Collapse and the Photoionization of the Inner 4d Shells for Xe-like Ions
K. T. Cheng and W. R. Johnson
Phys. Rev. A 28, 2820 (1983)

Energy-Level Scheme and Transition Probabilities of Cl-Like Ions
K.-N. Huang, Y.-K. Kim, K. T. Cheng, and J. P. Desclaux
At. Data and Nucl. Data Tables 28, 355 (1983)

Dependence of Multiple-Scattering Distributions on the Charge States of Fast Ions Exiting from Solid Targets
E. P. Kanter
Phys. Rev. A 28, 1401 (1983)

Electric Field Ionization of Foil-Excited Rydberg States of Fast Heavy Ions
E. P. Kanter, D. Schneider, and Z. Vager
Phys. Rev. A 28, 1193 (1983)

Coherent Stark Levels in Beam-Foil-Excited Fast Rydberg Atoms
Z. Vager, E. P. Kanter, D. Schneider, and D. S. Gemmell
Phys. Rev. Lett. 50, 954 (1983)

Apparatus for Measurements on the Fragmentation of MeV Molecular-Ion Beams
B. J. Zabransky, P. J. Cooney, D. S. Gemmell, E. P. Kanter, and Z. Vager
Rev. Sci. Instrum. 54, 531 (1983)

Ionization of Fast Foil-excited Ion Beams in Electromagnetic Fields
E. P. Kanter, D. Schneider, Z. Vager, D. S. Gemmell, B. J. Zabransky,
Gu Yuan-zhuang, P. Arcuni, P. M. Koch, D. R. Mariani, and W. Van de Water
Phys. Rev. A 29, 583 (1984)

Post-foil Interaction in the Foil-induced Dissociation of 3.25-MeV CH^+
I. Plesser, E. P. Kanter, and Z. Vager
Phys. Rev. A 29, 1103 (1984)

Projectile Ionization in Fast Heavy-Ion--Atom Collisions
D. Schneider, M. Prost, N. Stolterfoht, G. Nolte, and R. Du Bois
Phys. Rev. A 28, 649 (1983)

PUBLISHED REPORTS AT MEETINGS

The High-Energy Limit, Proceedings of the XVIII Course of the International School of Subnuclear Physics, 31 July-11 August 1980, Erice, Trapani, Sicily. (Plenum Press, N.Y. 1983) ed. Antonio Zichichi

Su(5) Without Su(5): Why B-L is Conserved and Baryon Number not in Unified Models of Quarks and Leptons
H. J. Lipkin
p. 281-302

Why Most Flavor Dependence Predictions for Non-Leptonic Charm Decays are Wrong
H. J. Lipkin
p. 389-409

Exotic Multiquark States with Charm
H. J. Lipkin
p. 599-617

Proceedings of a NATO Advanced Study Institute on Molecular Ions: Geometric and Electronic Structures, Kos, Greece, 30 September-10 October 1980, ed. J. Berkowitz and K.-O. Groeneveld, Plenum Publishing Co. 1983, Series B: Physics, Vol. 90

Determination of Molecular Ion Structures by Photoelectron Spectroscopy
G. L. Goodman and J. Berkowitz
p. 69-123

The Role of Excited States of Molecular Ions in Structure Studies with High Energy Collisions
E. P. Kanter
p. 463-509

Electron-Electron Correlation in Highly Charged Atoms
W. R. Johnson and K. T. Cheng
Quantum Electrodynamics of Strong Fields, ed. W. Greiner (Plenum Publishing Corp., 1983). Proc. of Conference on Quantum Electrodynamics of Strong Fields, Lahnstein/Rhein, Germany, 15-26 June 1981, p. 463-487

Proceedings of the Workshop on Relativistic Action at a Distance: Classical and Quantum Aspects, Barcelona, Spain, 15-21 June 1981, ed. J. Llosa, Lecture Notes in Physics No. 162, 1982

Forms of Relativistic Quantum Dynamics (Particles vs. Fields)
F. Coester
p. 50-65

Relativistic-Particle Quantum Mechanics (Applications and Approximations)
F. Coester
p. 66-74

Atomic Structure Calculations Using the Relativistic Random-Phase Approximation
K. T. Cheng
Abstract in Relativistic Effects in Atoms, Molecules, and Solids, Proc. of a NATO Advanced Study Institute of Relativistic Effects in Atoms, Molecules and Solids, Aug. 10-21, 1981, Univ. of British Columbia, Vancouver, B.C., ed. G. L. Malli (Plenum Press 1983), p. 505

Resonances in sd-Shell Nuclei
J. P. Schiffer
Proceedings of the Symposium on Resonances in Heavy Ion Reactions, Bad Honnef, 12-15 Oct. 1981. Lecture Notes in Physics No. 156, ed. K. A. Eberhard (Springer-Verlag 1982), p. 177-184

Carbon Stripper Foil Lifetime Tests
G. Thomas, P. Den Hartog, W. Henning, R. Pardo, J. Yntema, P. Maier-Komor, and D. Tolfree
Proceedings of the 10th World Conference of the International Nuclear Target Development Society, Rehovot, Israel, 19-23 October 1981, published by the Int. Nucl. Target Dev. Society 1983, p.1-16

A Study of 7.32-MeV and 9.88-MeV Levels of ^{38}K
C. M. Bhat, N. G. Puttaswamy, H. T. Fortune, and J. L. Yntema
Proceedings of the Nuclear Physics and Solid State Physics Symposium, Bhabha Atomic Research Centre, Bombay, India, 28 December-1 January 1982, Nucl. Phys. and Sol. State Phys. 24B, 21-22 (1981)

Search for Free Quarks at PEP
S. J. Freedman
Novel Results in Particle Physics-1982, Proceedings of the 5th International Conference on Novel Results in Particle Physics, Vanderbilt University, 24-26 May 1982, ed. R. S. Panvini, M. S. Alam, and E. Csorna. AIP Conference Proceedings 93, 24-33 (1982)

Proceedings of the 11th International Radiocarbon Conference, Seattle, Wa., 20-26 June 1982, Radiocarbon 25 (1983)

Accelerator Mass Spectrometry: From Nuclear Physics to Dating
Walter Kutschera
p. 677-691

Detection of the ^{36}Cl Radioisotope at the Rehovot 14UD Pelletron Accelerator
Michael Paul, Oded Meirav, Walter Henning, Walter Kutschera, Robert Kaim, Mark B. Goldberg, Jean Gerber, William Hering, Aaron Kaufman, and Mordeckai Magaritz
p. 785-792

Deformation and Collective Motion in the Very High Angular Momentum Region
T. L. Khoo
Proceedings of the Workshop on Development and Perspective on Inbeam Measurement of Particle-e-γ Spectroscopy and Particle-γ Correlation, Osaka Univ., 15-16 July 1982, ed. E. Ejiri and Y. Nagai, p. 147

Proceedings of the International Conference on Nuclear Structure, Amsterdam, The Netherlands, 30 August-3 September 1982, ed. A. Van der Woude and B. J. Verhaar, Nucl. Phys. A396 (1983)

Nuclear Structure in Pion Scattering and Charge Exchange
Benjamin Zeidman and Donald F. Geesaman
p. 419c-436c

Proceedings of the International Conference on Nuclear Structure, Amsterdam, The Netherlands, 30 August-3 September 1982 (Contd.)

Summary Talk
John P. Schiffer
497c-502c

Gamma-gamma Energy Correlations in Some Hf and W Isotopes
H. J. M. Aarts, H. F. R. Arciszewski, R. Holzmann, M. Huyse, R. V. F. Janssens, R. Kamermans, G. Lhersonneau, C. J. van de Poel, M. A. Van Hove, J. Vervier, and M. J. A. de Voigt
Volume of Abstracts, p. 192

Proceedings of the 6th Pan-American Workshop on Condensed Matter Theories, Feenberg Memorial Symposium, St. Louis, Mo., 20 Sept.--1 Oct. 1982, ed. J. M. C. Chen, J. W. Clark, P. Suntharothock-Priesmeyer

Relativistic Many-Body Systems with Direct Interactions
F. Coester
p. 2

Droplets of Liquid ^{4}He
Steven C. Pieper
p. 8

Three-Body Forces in Light Nuclei, Nuclear Matter and Neutron Stars
Robert B. Wiringa
p. 20

Classical Equations of Motion Calculations of High-Energy Heavy-Ion Collisions
A. R. Bodmer
p. 78

"Sandwich Targets" for Heavy Ion Experiments
George E. Thomas
Proceedings of the 11th World Conference of the International Nuclear Target Development Society, Seattle, Wa., 6-8 October 1982. University of Washington, Nuclear Physics Laboratory Report, 1983, p. 58

Proceedings of the International Conference on Nucleus-Nucleus Collisions, Michigan State University, 26 September-1 October 1982, ed. G. F. Bertsch, C. K. Gelbke, and D. K. Scott (North-Holland, Amsterdam)
Nucl. Phys. A400 (1983)

Research at the Argonne Linac
W. Henning
p. 295c-313c

Shell Model Studies of Very Neutron Deficient Ru and Rh Nuclei
A. Amusa and R. D. Lawson
Volume of Abstracts, p. 51

Proceedings of the Conference on High Angular Momentum Properties of Nuclei, Oak Ridge National Laboratory, 2-4 November 1982, Vol. 1 Abstracts, ORNL Informal Report, Vol. 2, Harwood Publishers, Nuclear Science Research Conference Series, ed. Noah R. Johnson

Band Structures in ^{186}Hg
R. V. F. Janssens, P. Chowdhury, H. Emling, D. Frekers, T. L. Khoo, W. Kühn, Y. H. Chung, P. J. Daly, Z. W. Grabowski, M. Kortelahti, J. MacNeil, J. Y. Zhang, and G. Leander
Vol. 1, p. 18

Shape Transitions at High Spin
T. L. Khoo, P. Chowdhury, H. Emling, D. Frekers, R. V. F. Janssens, W. Kühn, M. Kortelahti, A. Pakkannen, R. Broda, Y. H. Chung, P. J. Daly, Z. W. Grabowski, H. Helppi, F. Haas, J. Kasagi, R. M. Ronningen and F. Azgui
Vol. 1, p. 179

Gamma-Gamma Energy Correlations in $^{170,171}W$
H. F. R. Arciszewski, R. Holzmann, M. Huyse, R. V. F. Janssens, R. Kamermans, G. Lhersonneau, C. J. van der Poel, M. A. Van Hove, J. Vervier, M. J. A. de Voigt
Vol. 1, p. 84
Vol. 2, p. 375

Proceedings of the 1982 IEEE Conference on the Application of Accelerators in Research and Industry, North Texas State University, Denton, TX, 8-10 November 1982

Stopping Power for Fast Nitrogen and Oxygen DiClusters in Carbon
Malcolm F. Steuer, Donald S. Gemmell, Elliot P. Kanter, Edward A. Johnson, and Bruce J. Zabransky
IEEE Trans. Nucl. Sci. NS-30, 1069-1073 (1983)

Reduction of Ripple Voltage in a Dynamitron
Alexander Langsdorf, Jr.
IEEE Trans. Nucl. Sci. NS-30, 1453-1455 (1983)

A 145-MHz Niobium Split-Ring Resonator for Particle Velocities from 0.12 to 0.23 C
K. W. Shepard and G. P. Zinkann
Proceedings of the Applied Superconductivity Conference, Knoxville, TN, 30 November-3 December 1982
IEEE Trans. Magn. MAG-19, 1312-1314 (1983)

Proceedings of the Workshop on Atomic Physics with Fast Heavy-Ion Beams, Argonne National Laboratory, 20-21 January 1983, Argonne Laboratory Report CONF-830130 (1983).

Electron Spectroscopy with Fast Heavy Ion Beams
D. Schneider
p. 87-117

Heavy-ion Beam-pumped He-Ar, He-Xe, and Ar-Xe Gas Lasers
A. Ulrich, H. Bohn, P. Kienle, and G. J. Perlow
p. 261

1983 Particle Accelerator Conference, Santa Fe, New Mexico, 21-23 March 1983

The Argonne Tandem-Linac Accelerator System (ATLAS)
L. Bollinger
Bull. Am. Phys. Soc. 28, 90 (1983)
+ IEEE NS-30, 2065 (1983)

Conceptual Design of a 1.1 GeV 500μA Fast Cycling Proton Synchrotron
Y. Cho, E. Crosbie, T. Khoe, R. Kustom, R. Martin, W. Praeg, K. Thompson, and G. Wustefeld
Bull. Am. Phys. Soc. 28, 125 (1983)
+ IEEE NS-30, 2117 (1983)

Effect of Synchrotron Radiation in the Proposed 4 GeV Argonne Microtron
Edwin A. Crosbie
Bull. Am. Phys. Soc. 28, 103 (1983)
+ IEEE NS-30, 3218 (1983)

185 MeV Injector Design for the ANL 4 GeV Microtron Project
Eugene Colton
Bull. Am. Phys. Soc. 28, 104 (1983)
+ IEEE NS-30, 3232 (1983)

Transverse Beam Containment in the ANL 4 GeV Microtron
Eugene Colton
Bull. Am. Phys. Soc. 28, 104 (1983)
+ IEEE NS-30, 3221 (1983)

Antiproton Beam Transport in the Fermilab Tevatron I Project
Eugene Colton and Carlos Hojvat
Bull. Am. Phys. Soc. 28, 113 (1983)
+ IEEE NS-30, 2784 (1983)

Use of Axially Symmetric Electrostatic Fields for Ion Beam Focussing
Eugene Colton and J. C. Kelly
Bull. Am. Phys. Soc. 28, 15 (1983)
+ IEEE NS-30, 2734 (1983)

Design for an Argonne Super Intense Pulsed Neutron Source
R. L. Kustom and T. K. Khoe
Bull. Am. Phys. Soc. 28, 91 (1983)
+ IEEE NS-30, 2086 (1983)

Analytical Study of the Generation and Control of Orbit Errors in the ANL 4 GeV C.W. Electron Microtron Design
R. L. Kustom
Bull. Am. Phys. Soc. 28, 104 (1983)
+ IEEE NS-30, 3229 (1983)

GEM, ANL 4 GeV, CW Electron Microtron Design
R. L. Kustom
Bull. Am. Phys. Soc. 28, 147 (1983)
+ IEEE NS-30, 3286 (1983)

High Charge Picosecond Pulses with a Double Gap Subharmonic Buncher
G. Mavrogenes, W. Gallagher, T. Khoe, and D. Ficht
Bull. Am. Phys. Soc. 28, 130 (1983)
+ IEEE NS-30, 2989 (1983)

120-GeV Proton Transport for Antiproton Production in the Fermilab Tevatron I Project
Eugene Colton, Carlos Hojvat, and Les Oleksiuk
Bull. Am. Phys. Soc. 28, 160 (1983)
+ IEEE NS-30, 2818 (1983)

Multisided Microtron Design Studies
T. K. Khoe
Bull. Am. Phys. Soc. 28, 104 (1983)

Energy Measurement and Regulation Using a Resonator Based Time-of-Flight System
R. C. Pardo, R. N. Lewis, K. W. Johnson, and B. Clifft
Bull. Am. Phys. Soc. 28, 151 (1983)
+ IEEE NS-30, 2237 (1983)

A Superconducting Accelerating Structure for Particle Velocities from 0.12 to 0.23 C
K. W. Shepard and G. P. Zinkann
Bull. Am. Phys. Soc. 28, 93 (1983)
+ IEEE NS-30, 3339 (1983)

Annual Meeting of the German Physical Society, Munster, W. Germany, 21-15 March 1983

Time Structure of the Feeding into High Spin States in $^{152,154}Dy$
F. Azgui, P. Chowdhury, Y. H. Chung, P. Daly, D. Frekers, C. Grabowski, R. V. F. Janssens, T. L. Khoo, M. Korthelati, W. Kühn, and A. Pakkanen
Verhandl. Dent. Physik. Ges. 5, 1072 (1983)

Lifetime Measurements in the Ground-State Rotational Band in ^{159}Tb
M. A. Van Hove, Y. El Masri, R. Holtmann, R. V. F. Janssens, C. Michel, J. Vervier
Verhandl. Dent. Physik. Ges. 5, 1141 (1983)

Ideas on Future Large γ-Detector Arrays at Argonne
T. L. Khoo, R. V. F. Janssens, U. Garg, J. Kolata, E. Funk and J. Mihelich
Proceedings of Workshop on "Physics with Large Gamma Detector Arrays," AECL-MISC-251 (Unpublished informal report of Chalk River Nuclear Labs., McMaster University, 9-10 April 1983)

APS Meeting, Baltimore, Md., 18-21 April 1983

The ^{7}Be Decay Branching Ratio
C. N. Davids, A. J. Elwyn, B. W. Filippone, S. B. Kaufman, K. E. Rehm, and J. P. Schiffer
Bull. Am. Phys. Soc. 28, 714 (1983)

Resonances in $^{7}Be(\alpha,\gamma)$ and $^{7}Li(\alpha,\gamma)$
A. J. Elwyn, B. Filippone, G. Hardie, R. E. Segel, and M. Wiescher
Bull. Am. Phys. Soc. 28, 650 (1983)

Neutron β Decay
S. J. Freedman, P. Bopp, D. Dubbers, Y. Last, H. Schutze, and O. Scharpf
Bull. Am. Phys. Soc. 28, 713 (1983)

On the Validity of the Parabolic Approximation in the Calculation of Cross Sections for Heavy Ion Reactions
W. Freeman and J. P. Schiffer
Bull. Am. Phys. Soc. 28, 745 (1983)

Properties of Nuclear Shapes in Light Hg-Isotopes at High Spin
D. Frekers, P. Chowdhury, H. Emling, R. V. F. Janssens, T. L. Khoo, R. Broda, Y. H. Chung, P. J. Daly, Z. W. Grabowski, H. Helppi, M. Kortelahti, S. Frauendorf, and Z. Y. Zhang
Bull. Am. Phys. Soc. 28, 687 (1983)

Cosmic Ray Backgrounds and Neutrino Oscillation Experiments
G. T. Garvey, J. Napolitano, S. J. Freedman, M. Kroupa, and J. Worthington
Bull. Am. Phys. Soc. 28, 755 (1983)

Pion Inelastic Scattering to Isoscalar Spin-Flip Excitations
D. F. Geesaman
Bull. Am. Phys. Soc. 28, 740 (1983)

Coincidence Measurements Between Evaporation-Residues and Light Particles Produced in $^{16}O + {}^{24}Mg$ at $E_{lab}(^{16}O) = 150$ MeV
D. G. Kovar, R. V. F. Janssens, W. Kühn, R. Betts, P. Chowdhury, D. Henderson, T. Humanic, H. Ikezoe, G. Rosner, and K. Wolf
Bull. Am. Phys. Soc. 28, 670 (1983)

Measurements of Long Half-Lives with Accelerator Mass Spectrometry
W. Kutschera, D. Frekers, W. Henning, R. Pardo, K. E. Rehm, R. K. Smither, J. L. Yntema, X. Z. Ma, L. F. Mausner, M. Paul, and B. Stievano
Bull. Am. Phys. Soc. 28, 714 (1983)

Pion Double Charge Exchange on ^4He
R. D. McKeown, J. E. Ungar, D. Geesaman, R. Holt, J. Specht, K. Stephenson, B. Zeidman, and C. Morris
Bull. Am. Phys. Soc. 28, 671 (1983)

The Alpha Width of the 2^-(5.11 MeV) State in ^{10}B: Implication for $\Delta I=1$ Parity Violation in Nuclei
J. Napolitano and S. J. Freedman
Bull. Am. Phys. Soc. 28, 650, (1983)

Study of Direct Reactions in the System $^{37}Cl + {}^{208}Pb$
K. E. Rehm, D. Kovar, W. Kutschera, M. Paul, G. Stephans, and J. L. Yntema
Bull. Am. Phys. Soc. 28, 731 (1983)

Search for Incomplete Fusion in $^{28}Si + {}^{12}C$, ^{24}Mg, ^{27}Al, ^{28}Si, ^{40}Ca and $^{16}O + {}^{24}Mg$, ^{28}Si, ^{40}Ca
G. Rosner, D. G. Kovar, P. Chowdhury, D. Henderson, H. Ikezoe, R. V. F. Janssens, W. Kühn, G. S. Stephans, B. Wilkins, F. Prosser, Jr., J. Kolata, and J. Hinnefeld
Bull. Am. Phys. Soc. 28, 670 (1983)

A Cryogenic Search for Fractional Charge
J. P. Schiffer, D. Frekers, W. Henning, W. Kutschera, K. W. Shepard, C. Curtis, and C. Schmidt
Bull. Am. Phys. Soc. 28, 709 (1983)

Measurement of Tensor Polarization in Elastic Electron-Deuteron Scattering
M. Schulze, D. Beck, W. Bertozzi, M. Farkondeh, S. Gilad, S. Kowalski, R. Redwine, W. Turchinetz, R. Holt, J. Specht, K. Stephenson B. Zeidman, E. Stephenson, J. Moses, R. Goloskie, D. Saylor, M. Leitch
Bull. Am. Phys. Soc. 28, 673 (1983)

Elastic and Inelastic Scattering, and Single-Nucleon Transfer Reactions Observed in $^{16}O + {}^{40}Ca$ at $E_{lab}(^{16}O) = 150$ MeV
G. S. F. Stephans, D. G. Kovar, H. Ikezoe, R. Pardo, K. E. Rehm, and G. Rosner
Bull. Am. Phys. Soc. 28, 717 (1983)

Measurement of t_{20} in π^{+}-d Elastic Scattering Between 134 and 256 MeV
E. Ungricht, W. S. Freeman, D. F. Geesaman, R. J. Holt, J. R. Specht, B. Zeidman, E. J. Stephenson, J. D. Moses, M. Farkhondeh, S. Gilad, and R. Redwine
Bull. Am. Phys. Soc. 28, 718 (1983)

Proceedings of the 6th Tandem Conference, Daresbury Laboratory, Chester, England, 18-22 April 1983

The Argonne Inverted Sputter Source
J. L. Yntema and P. J. Billquist
Nucl. Instrum. Methods 220, 107-108 (1984)

Search for Doubly-Charged Negative Ions via Accelerator Mass Spectrometry
Walter Kutschera, Dieter Frekers, Richard Pardo, Karl E. Rehm, Robert K. Smither, and Jan L. Yntema
Nucl. Instrum. Methods 220, 118-122 (1984)

Proceedings of the Conference on New Horizons in Electromagnetic Physics, University of Virginia, Charlottesville, Va., April 21-24, 1982, ed. J. V. Noble and R. R. Whitney

Conceptual Design of a 4 GeV Hexogonal Microtron
T. K. Khoe
p. 502

Conceptual Design for a 2 GeV C.W. Electron Microtron
Robert Kustom
p. 505

Meson-exchange Hamiltonian for NN Scattering and Isobar-nucleus Dynamics
T.-S. H. Lee
Proceedings of the Symposium on Delta-Nucleus Dynamics, 2-4 May 1983, Argonne National Laboratory. Argonne Report No. ANL-PHY-83-1 (Oct. 1983), ed. T.-S. H. Lee, D. F. Geesaman, and J. P. Schiffer, p. 199-217

Plans for Data Acquisition for the New Accelerator, ATLAS
Lester C. Welch
Proc. of the Conference on Real-Time Computer Applications in Nuclear and Particle Physics, 16-19 May 1983, Berkeley, CA
IEEE Trans. Nucl. Sci. NS-30(5), 3921-3924 (1983)

APS Meeting, Division of Electron and Atomic Physics, Boulder, CO, 23-25 May 1983

Molecular Dissociation of CN^{+} Ions from a Tandem Accelerator
H. G. Berry, L. Engstrom, S. Huldt, R. Hellborg, and I. Martinson
Bull. Am. Phys. Soc. 28, 801 (1983)

Collapse of the 4f Orbital for Xe-like Ions
K. T. Cheng and C. Froese Fischer
Bull. Am. Phys. Soc. 28, 813 (1983)

Fine Structure of Doubly Excited States in Ne VII and Ne VIII
J. E. Hardis, H. G. Berry, A. E. Livingston, L. J. Curtis, and
P. S. Ramanujan
Bull. Am. Phys. Soc. 28, 790 (1983)

2s-2p Transitions in Ti XXI
J. E. Hardis, H. G. Berry, L. P. Somerville, D. Neek, and
A. E. Livingston
Bull. Am. Phys. Soc. 28, 790 (1983)

10th International Conference on Atomic Collisions in Solids, Bad Iburg, Germany, July 18-22, 1983, Book of Abstracts

Auger Yields from Thin Si- and Au-Targets Excited by Fast (MeV) H+ Impact
D. Schneider, H. Kudo, and P. Arcuni
p. 154

Ionization of Fast Foil-Excited Ion Beams in Electromagnetic Fields
E. P. Kanter, D. Schneider, D. S. Gemmell, B. J. Zabransky,
P. Arcuni, and Z. Vager
p. 3

13th International Conference on the Physics of Electronic and Atomic Collisions, Berlin, Germany, 27 July-2 August 1983, Book of Abstracts, ed. J. Eichler, W. Fritsch, I. V. Hertel, N. Stolterfoht, and U. Wille

UV-Laser Photodissociation of Molecular Ions
R. E. Kutina, A. K. Edwards, and J. Berkowitz
p. 57

Auger Electron Emission Following Fast (MeV) Molecular- and Atomic-Ion Impact on Thin C-Foils
D. Schneider, E. P. Kanter, and B. J. Zabransky
p. 382

Autoionization Spectra of He Excited by Fast (MeV) H^+, He^+, and Li^{n+} (n = 1,2,3) Ions
D. Schneider, P. Arcuni, R. Bruch, and W. Stöffler
p. 383

Autoionization of Fast (MeV) Li-Ions Incident on Gases and C-Foils
D. Schneider, P. Arcuni, R. Bruch, W. Stoffler, and C. F. Moore
p. 384

13th International Conference on the Physics of Electronic and Atomic Collisions, Berlin, Germany, 27 July-2 August 1983 (Contd.)

Electric Field-Ionization of Rydberg States of Fast Foil-Excited Sulphur Ions
E. P. Kanter, D. Schneider, Z. Vager
p. 667

Proceedings of the International Conference on Nuclear Physics, Florence, Italy, August 29-September 3, 1983, (Tipografia Compsoitori-Bologna), Vol. 1

Measurement of Tensor Polarization in Pion-Deuteron Elastic Scattering
W. S. Freeman, D. F. Geesaman, R. J. Holt, J. R. Specht, E. Ungricht, B. Zeidman, E. J. Stephenson, J. D. Moses, M. Farkhondeh, S. Gilad, and R. P. Redwine
p. 24

Yrast $(\pi h_{11/2})^4$ States in the Four Valence Proton N = 82 Nucleus ^{150}Er
Y. H. Chung, R. Broda, P. J. Daly, S. R. Faber, Z. W. Grabowski, H. Helppi, M. Kortelahti, A. Pakkanen, P. Chowdhury, R. V. F. Janssens, T. L. Khoo, R. D. Lawson, J. Blomqvist
p. 70

E2 Transition Rates Between $(\pi h_{11/2})^n$ States of the Same Seniority
P. J. Daly, Y. H. Chung, Z. W. Grabowski, H. Helppi, M. Kortelahti, P. Chowdhury, R. V. F. Janssens, T. L. Khoo, R. D. Lawson, and J. Blomqvist
p. 73

A Transition from Collective to Few-Particle Yrast Configurations at High Angular Momentum by ^{153}Dy
M. Kortelahti, R. Broda, Y. H. Chung, P. J. Daly, J. McNeill, A. Pakkanen, P. Chowdhury, R. V. F. Janssens, T. L. Khoo, W. Kühn
p. 159

Lifetimes of High Spin States in ^{181}Ir and ^{180}Os
R. Kaczarowski, A. Chaudhury, E. G. Funk, U. Garg, J. W. Mihelich, D. Frekers, R. V. F. Janssens, and T. L. Khoo
p. 181

The Beta Decay of the $J^{\pi} = 0^-$ First Excited State of ^{16}N and Weak Axial Vector Meson Exchange Currents
S. J. Freedman, C. A. Gagliardi, G. T. Garvey, and J. R. Wrobel
p. 715

Radioisotope Detection by Accelerator Mass-Spectrometry at the Rehovot 14 UD Pelletron
M. Paul, H. Ernst, W. Henning, W. Kutschera, O. Meirav, R. Kaim, M. B. Goldberg, M. Margaritz
p. 756

13th International Conference on the Physics of Electronic and Atomic Collisions, Berlin, Germany, 27 July-2 August 1983 (Contd.)

The Measurement of Long Half-Lives with Accelerator Mass Spectrometry
W. Kutschera, P. J. Billquist, D. Frekers, W. Henning, X. Z. Ma, L. F. Mausner, R. Pardo, M. Paul, K. E. Rehm, R. K. Smither, B. Stievano, and J. L. Yntema
p. 754

APS Fall Meeting of the Division of Nuclear Physics, Notre Dame, Indiana, 13-15 October 1983

Weak Neutral-Current Effects in Electron-Scattering Coincidence Experiments
W. E. Kleppinger
Bull. Am. Phys. Soc. 28, 965 (1983)

Coincidence Measurements Between Evaporation Residues and Light Particles Produced in $^{16}O + ^{40}Ca$ at $E_{lab}(^{16}O) = 160$ MeV
H. Ikezoe, D. G. Kovar, G. Rosner, G. Stephans, E. Ungricht, B. Wilkins, T. Awes, G. Young, C. Maguire, Z. Kui, W. C. Ma, S. Robinson, D. Watson, and G. Word
Bull. Am. Phys. Soc. 28, 974 (1983)

Isomers in Proton Rich Nuclei Near N = 82
R. Broda, Y. H. Chung, P. J. Daly, Z. W. Grabowski, H. Helppi, M. Kortelahti, J. McNeill, P. Chowdhury, R. V. F. Janssens, and T. L. Khoo
Bull. Am. Phys. Soc. 28, 981 (1983)

Quasielastic Processes in the $^{28}Si + ^{40}Ca$ and $^{28}Si + ^{208}Pb$ Reactions at 8 MeV/A
J. J. Kolata, R. J. Vojtech, G. S. F. Stephans, D. G. Kovar, K. E. Rehm, G. Rosner, and H. Ikezoe
Bull. Am. Phys. Soc. 28, 995 (1983)

Seniority-Four Yrast States in the N = 82 Nucleus ^{150}Er
Y. H. Chung, R. Broda, P. J. Daly, S. R. Faber, Z. W. Grabowski, H. Helppi, M. Kortelahti, A. Pakkanen, P. Chowdhury, R. V. F. Janssens, T. L. Khoo, R. D. Lawson, and J. Blomqvist
Bull. Am. Phys. Soc. 28, 982 (1983)

High-Spin States in the N = 83 Nucleus ^{152}Tm
J. McNeill, R. Broda, Y. H. Chung, P. J. Daly, Z. W. Grabowski, H. Helppi, M. Kortelahti, P. Chowdhury, R. F. F. Janssens, T. L. Khoo, and R. D. Lawson
Bull. Am. Phys. Soc. 28, 982 (1983)

RDM Measurements for High Spin States in ^{181}Ir and ^{180}Os
R. Kaczarowski, A. Chaudhury, E. G. Funk, U. Garg, J. W. Mihelich, D. Frekers, R. V. F. Janssens, T. L. Khoo
Bull. Am. Phys. Soc. 28, 989 (1983)

1984 Spring Meeting of the American Physical Society, Washington, D.C., April 23-26, 1984

Coupled Channels Analysis of Single and Mutual Inelastic Scattering of $^{28}Si + ^{28}Si$
F. Videbaek, P. R. Christensen, S. Saini, R. R. Betts, B. B. Back, I. Ahmad, B. D. Wilkins, S. Pieper, P. D. Bond, Ole Hansen, M. J. Levine, C. E. Thorn, and M. J. McFarlane
Bull. Am. Phys. Soc. 29, 625 (April 1984)

Study of Large-Angle Yields from $^{16}O + ^{40,44}Ca$ Reactions
S. J. Sanders, R. R. Betts, S. Saini, F. Videbaek, I. Ahmad, D. Henderson, K. Lesko, B. Wilkins, and B. Dichter
Bull. Am. Phys. Soc. 29, 625 (April 1984)

$^{88}Sr(\vec{p},\pi^-)$ to High Spin, 2p-1h States in ^{89}Zr
M. C. Green, J. D. Brown, W. W. Jacobs, E. Korkmaz, T. G. Throwe, S. E. Vigdor, T. E. Ward, and P. L. Jolivette
Bull. Am. Phys. Soc. 29, 627 (April 1984)

The Beta Decay of the Free Neutron
S. J. Freedman
Bull. Am. Phys. Soc. 29, 666 (April 1984)

Investigation of the Transition from Quasi-elastic to Deep-inelastic Processes in the Systems $^{46,48,50}Ti + ^{208}Pb$
K. E. Rehm, A. M. Van den Berg, J. Kolata, D. G. Kovar, W. Kutschera, G. Rosner, G. Stephans, and J. L. Yntema
Bull. Am. Phys. Soc. 29, 673 (April 1984)

Two-Body Pion Absorption in ^{3}He
S. Levenson, R. Segel, S. Mukhopadhyay, D. Ashery, D. Geesaman, J. Schiuffer, G. Stephans, E. Ungricht, B. Zeidman, E. Piasetzky, R. Minehart, R. Whitney, G. Das, C. Smith, R. Madey, B. Anderson, J. Watson, and R. McKeown
Bull. Am. Phys. Soc. 29, 674 (April 1984)

Study of Quasielastic Processes in Reactions Between Medium Weight Nuclei
K. E. Rehm, A. M. Van den Berg, J. Kolata, D. G. Kovar, W. Kutschera, G. Rosner, G. STephans, and J. Yntema
Bull. Am. Phys. Soc. 29, 674 (April 1984)

Evidence for Three Body Pion Absorption in $^{3}He(\pi^+,3p)$
D. Ashery, D. Geesaman, J. Schiffer, G. Stephans, E. Ungricht, B. Zeidman, S. Levenson, R. Segel, S. Mukhopadhyay, E. Piasetzky, R. Minehart, R. Whitney, G. Das, C. Smith, R. Madey, B. Anderson, J.Watson, and R. McKeown
Bull. Am. Phys. Soc. 29, 674 (April 1984)

Backbending in the $1/2^-[541]$ Band in ^{181}Ir
U. Garg, A. Chaudhury, E. G. Funk, R. Kaczarowski, J. W. Mihelich, D. Prekers, R. V. F. Janssens, and D. Radford
Bull. Am. Phys. Soc. 29, 719 (April 1984)

Search for Magnetic Monopoles in Cosmic Rays
M. Kroupa, S. J. Freedman, J. Napolitano, J. Dawson, and B. Gobbi
Bull. Am. Phys. Soc. 29, 735 (April 1984)

Precise Spin-rotation and Hyperfine Constants of the B and X States of the CaI Radical
L. S. Goodman, W. J. Childs, and V. Pfeufer
Bull. Am. Phys. Soc. 29, 737 (April 1984)

A Search for Scalar Particles Emitted in Nuclear Decay
J. Napolitano, S. J. Freedman, M. Kroupa, and J. Camp
Bull. Am. Phys. Soc. 29, 748 (April 1984)

Measurement of Fission Cross Sections in $^{58,64}Ni + ^{112-124}Sn$
K. Lesko, G. Rosner, W. Henning, K. E. Rehm, J. Schiffer, G. Stephans, and B. Zeidman
Bull. Am. Phys. Soc. 29, 756 (April 1984)

Momentum Transfer in ^{14}N Induced Fusion Reactions Between 5.5 and 35 MeV/A
G. S. F. Stephans, D. G. Kovar, G. Rosner, H. Ikezoe, R. V. F. Janssens, B. Wilkins, K. T. Lesko, J. J. Kolata, K. Gelbke, B. Jacak, Z. Koenig, G. Westfall, R. Fox, C. Chitwood, P. Gonthier, A. S. de Toledo, and E. Szanto
Bull. Am. Phys. Soc. 29, 757 (April 1984)

C. ANL PHYSICS DIVISION REPORTS

Electron Scattering
John Dirk Walecka
Argonne Report ANS-83-50. Lectures given at Argonne National Laboratory between October 1982 and January 1983

Proceedings of the Symposium on Delta-Nucleus Dynamics
Argonne National Laboratory, May 2-4, 1983, Argonne Report PHY-83-1, CONF-830588, ed. T.-S. H. Lee, D. F. Geesaman, and J. P. Schiffer

Proceedings of the Workshop on Atomic Physics with Fast Heavy-Ion Beams
Argonne National Laboratory, 20-21 January 1983, ANL Laboratory Report CONF-830130

Distribution for ANL-84-24

Internal:

R. Avery
L. Burris
D. W. Cissel
P. M. Dehmer
M. Derrick
R. E. Diebold
F. Y. Fradin
A. Friedman
E. Huberman
M. Inokuti
K. L. Kliewer
C. E. Klotz
A. B. Krisciunas (12)
L. G. LeSage
R. A. Lewis
P. Messina
E. G. Pewitt
W. H. Rauckhorst
J. J. Roberts
R. K. Smither
R. W. Springer
A. F. Stehney
E. P. Steinberg
C. E. Till
R. S. Zeno
R. Benaroya
J. Berkowitz
H. G. Berry
J. Bogaty
A. R. Bodmer
L. M. Bollinger
K. T. Cheng
W. J. Childs
F. Coester
R. E. Combs
E. A. Crosbie
C. N. Davids
P. K. Den Hartog
Dynamitron
M. S. Freedman
S. J. Freedman
G. T. Garvey
D. F. Geesaman
D. S. Gemmell (65)
L. S. Goodman
J. Greene
W. Henning
R. J. Holt
H. E. Jackson
R. V. F. Janssens
E. P. Kanter
T. K. Khoe
T.-L. Khoo
G. Klimczak
W. Koenig
D. G. Kovar
R. Kowalczyk
D. Kurath
R. L. Kustom
W. Kutschera
T.-S. H. Lee
J. E. Monahan
J. J. Napolitano
J. E. Nelson
R. C. Pardo
G. J. Perlow
M. Peshkin
S. C. Pieper
K. E. Rehm
G. R. Ringo
J. P. Schiffer
K. W. Shepard
J. R. Specht
K. J. Thayer (96)
G. E. Thomas
Z. Vager
L. C. Welch
R. B. Wiringa
J. L. Yntema
L. Young
B. Zabransky
B. Zeidman
ANL Patent Dept.
ANL Contract File
ANL Libraries
TIS Files (6)

External:

DOE-TIC, for distribution per UC-34 (93)
Manager, Chicago Operations Office, DOE
Physics Division Review Committee:
E. G. Adelberger, U. Washington
U. Fano, U. Chicago
L. C. Feldman, Bell Lab., Murray Hill
J. D. Fox, Florida State U.
W. Happer, Jr., Princeton U.
P. Kienle, GSI, Darmstadt, West Germany
S. E. Koonin, California Inst. Technology
D. F. Measday, U. British Columbia
S. A. Rice, U. Chicago
Antioch College, Olive Kettering Library, Antioch, Ill.
B. Bayman, U. Minnesota
G. B. Beard, Wayne State U.
B. Bederson, New York U.
C. H. Blanchard, U. Wisconsin-Madison
H. E. Blosser, Michigan State U.
R. L. Boudrie, Los Alamos National Lab.

T. J. Bowles, Los Alamos National Lab.
D. A. Bromley, Yale U.
Brooklyn College, Dept. of Physics
G. E. Brown, SUNY at Stony Brook
D. L. Bushnell, Northern Illinois U.
California State U., Dept. of Physics, Los Angeles
L. E. Campbell, Hobart & William Smith Colleges
P. Caruthers, Los Alamos National Lab.
Catholic University of America, Keane Physics Research Center
J. Cerny III, Lawrence Berkeley Lab.
Chemical Abstracts Service, Columbus
G. F. Chew, Lawrence Berkeley Lab.
W. A. Chupka, Yale U.
Cincinnati, U. of, Physics Library
J. W. Clark, Washington U.
C. M. Class, Rice U.
T. B. Clegg, U. North Carolina
S. Cohen, Speakeasy Computing Corp., Chicago
D. R. Cok, Eastman Kodak Research Labs., Rochester, N.Y.
Colorado, U. of, Nuclear Physics Lab.
P. J. Cooney, Millersville State College, Millersville, Pa.
Cornell U., Library
N. Cue, SUNY at Albany
S. E. Darden, U. Notre Dame
Dartmouth College, Library
P. T. Debevec, U. Illinois, Urbana
D. Dehnhard, U. Minnesota
Denver, U. of, Physics Dept.
R. M. DeVries, Los Alamos National Lab.
B. Donnally, Lake Forest College, Lake Forest, Ill.
T. R. Donoghue, Ohio State U.
A. K. Edwards, U. Georgia
A. J. Elwyn, Fermi National Accelerator Lab.
G. N. Epstein, Massachusetts Inst. Technology
B. W. Filippone, California Inst. Technology
Ford Aerospace and Communications Corp., Newport Beach, Calif.
H. T. Fortune, U. Pennsylvania
J. L. Fowler, Oak Ridge National Lab.
W. A. Fowler, California Inst. Technology
C. A. Gagliardi, Texas A&M U.
P. W. Gilles, U. Kansas
N. K. Glendenning, Lawrence Berkeley National Lab.
H. E. Gove, U. Rochester
W. Haeberli, U. Wisconsin, Madison
I. Halpern, U. Washington
M. Hamermesh, U. Minnesota
S. S. Hanna, Stanford U.
A. O. Hanson, U. Illinois, Champaign
B. G. Harvey, Lawrence Berkeley National Lab.
E. M. Henley, U. Washington
R. G. Herb, National Electrostatics Corp., Middleton, Wis.
R. E. Holland, Downers Grove, Ill.
V. W. Hughes, Yale U.
J. R. Huizenga, U. Rochester

IIT Research Institute, Physics Library, Chicago
Illinois, U. of, Dept. of Physics, Chicago
Indiana U., Cyclotron Project
M. Inghram, U. Chicago
D. R. Inglis, U. Massachusetts
Institute for Advanced Study, Physics Preprint Library, Princeton
P. B. Kahn, SUNY at Stony Brook
R. J. Kandel, Office of Basic Energy Sciences, USDOE
B. D. Keister, Carnegie-Mellon U.
A. K. Kerman, Massachusetts Inst. Technology
J. J. Kolata, U. Notre Dame
N. Koller, Rutgers U.
F. T. Kuchnir, Elmhurst, Ill.
R. O. Lane, Ohio U.
A. Langsdorf, Jr., Schaumburg, Ill.
L. L. Lee, Jr., SUNY at Stony Brook
J. J. Livingood, Hinsdale, Ill.
A. E. Livingston, U. Notre Dame
L. F. Long, U. Notre Dame
Louisiana State U., Dept. of Physics and Astronomy, Librarian
Louisiana State U., Director, Nuclear Science Center
M. H. Macfarlane, Indiana U.
Marquette U., Physics Dept., Milwaukee
J. V. Martinez, Office of Basic Energy Sciences, USDOE
Maryland, U. of, Dept. of Physics and Astronomy, Preprint Lib.
Massachusetts Inst. Technology, Physics Reading Room
R. D. McKeown, California Inst. Technology
Michigan State U., Cyclotron Lab., Librarian
Mississippi, U. of, Library
C. F. Moore, U. of Texas at Austin
F. P. Mooring, Glen Ellyn, Ill.
J. Negele, Massachusetts Inst. Technology
J. A. Nolen, Jr., Michigan State U.
W. K. H. Panofsky, Stanford Linear Accelerator Center
E. S. Pierce, Office of Basic Energy Sciences, USDOE
R. E. Pollock, Indiana U.
R. S. Preston, Northern Illinois U.
F. W. Prosser, Jr., U. Kansas
S. Raboy, Harpur College, SUNY, Binghamton
J. L. Rainwater, Columbia U., Irvington
M. Rhoades-Brown, SUNY at Stony Brook
R. G. H. Robertson, Los Alamos National Lab.
Rochester, U. of, Physics/Optics/Astronomy Lib.
N. P. Samios, Brookhaven National Lab.
R. P. Scharenberg, Purdue U.
R. M. Schectman, U. Toledo
A. Schwarzschild, Brookhaven National Lab.
R. E. Segel, Northwestern U.
K. K. Seth, Northwestern U.
S. M. Shafroth, U. North Carolina
C. P. Slichter, U. Illinois, Urbana
H. E. Stanton, Oak Lawn, Ill.
N. Stein, Los Alamos National Lab.
E. J. Stephenson, Indiana U.

M. F. Steuer, U. Georgia
J. Stoltzfus, Beloit College
G. E. Thomas, El Paso, Ill.
C. C. Trail, Brooklyn College
T. L. Tullos, Texas A&M U.
R. Vandenbosch, U. Washington
S. E. Vigdor, Indiana U.
J. D. Walecka, Stanford U.
T. P. Wangler, Los Alamos National Lab.
V. Weisskopf, Massachusetts Inst. Technology
W. R. Wharton, Carnegie-Mellon U.
M. G. White, Princeton U.
E. P. Wigner, Princeton U.
Wisconsin, U. of, Physics Library, Madison
C. S. Wu, Columbia U.
J. J. Wynne, IBM, Thomas J. Watson Research Center, Yorktown Heights, N. Y.
A. J. F. Boyle, U. Western Australia, Nedlands
L. T. Chadderton, David Rivett Lab., Clayton, Australia
J. C. Kelley, U. New South Wales, Kensington, Australia
A. Minchinton, Rose Park, Australia
J. O. Newton, Australian National U., Canberra
T. R. Ophel, Australian National U., Canberra
L. J. Tassie, Australian National U., Canberra
E. W. Titterton, Australian National U., Canberra
Vienna, U. of, Zentralbibliothek d. Physik Inst., Vienna, Austria
Euratom, Central Bu. Nuclear Measurements, Library, Geel, Belgium
Katholieka Universiteit Leuven, Inst. voor Theoretische Fysica, Heverlee, Belgium
J. Vervier, U. Catholique de Louvain, Belgium
Brasilia, Universidade de, Inst. Central de Fisica, Brazil
Divisao de Estudos Avancados, San Jose dos Campos, Brazil
O. Sala, Universidade de Sao Paulo, Brazil
Sao Paulo, Universidade de, Nuclear Physics Lib., Brazil
Universidade Federal de Pernambuco, Recife, Brazil
Alberta, U. of, Nuclear Research Centre, Dept. of Physics, Edmonton, Canada
R. L. Brooks, U. Guelph, Canada
H. C. Evans, Queens U., Kingston, Canada
D. Frekers, TRIUMF Lab., Vancouver, Canada
J. C. Hardy, Atomic Energy of Canada Ltd., Chalk River, Canada
T. J. Kennett, McMaster U., Hamilton, Canada
McGill U., Lib., Rutherford Physics Bldg., Montreal, Canada
G. C. Nielson, U. Alberta, Edmonton, Canada
Chile, U. of, Dept. of Physics, Santiago
D. Dazhao, Beijing, People's Republic of China
Y-z. Gu, Fudan University, Shanghai, People's Republic of China
J-s. Maa, National Tsing-Hua U., Hsinchu, Republic of China
P-K. Tseng, National Taiwan U., Taipei, Republic of China
J. U. Andersen, U. Aarhus, Denmark
A. Bohr, Inst. for Theoretical Physics, Copenhagen, Denmark
J. Borggreen, Niels Bohr Inst., Roskilde, Denmark
C. J. Christensen, Danish AEC, Risø, Denmark
B. R. Mottelson, Inst. for Theoretical Physics, Copenhagen, Denmark
Niels Bohr Inst., The Library, Copenhagen, Denmark
E. Nielsen, U. Aarhus, Denmark
O. Poulsen, U. Aarhus, Denmark

F. El Bedewi, Atomic Energy Establishment, Cairo, Egypt
M. El Nadi, Cairo U., Egypt
I. Hamouda, Atomic Energy Establishment, Cairo, Egypt
A. Osman, Cairo U., Egypt
Berkeley Nuclear Labs., Central Electricity Generating Bd., Librarian, England
Culham Lab., UKAEA, Librarian, England
Daresbury Laboratory, Information Officer, England
J. H. D. Eland, U. Oxford, England
A. T. G. Ferguson, AERE, Harwell, England
C. E. Johnson, U. Liverpool, England
J. S. Lilley, Daresbury Lab., England
Manchester, U. of, Dept. of Physics, England
G. C. Morrison, U. Birmingham, England
Sussex, U. of, Library, Brighton, England
University College London, Library, Dept. of Physics and Astronomy, England
K. V. Laurikainen, U. Helsinki, Finland
A. Abragam, CEN Saclay, France
P. Catillion, CEN Saclay, France
CEA Saclay, Library, France
Centre de Recherches Nucleaires, Library, Strasbourg, France
C.N.R.S., Centre de Physique Theorique, Preprint Lib., Marseille, France
C.N.R.S., Lab. de Physique Nucleaire, Strasbourg, France
J. Delaunay, CEN Saclay, France
Inst. de Physique Nucleaire, Lib., U. Paris, Orsay, France
Institut des Sciences Nucleaires, Lib., Grenoble, France
Laboratoire de l'Accelerateur Lineaire, U. Paris, Orsay, France
Laboratoire Souterrain de Modane, France
A. Michaudon, C.E.A., Centre d'Etudes de Bruyeres le Chatel, Montrouge, France
H. Nifenecker, CEN Grenoble, France
J. C. Poizat, U. Claude Bernard, Villeurbanne, France
J. M. Remillieux, U. Claude Bernard, Villeurbanne, France
K. Bethge, Universität Frankfurt, Germany
R. Bock, GSI, Darmstadt, Germany
Deutsches Elektronen-Synchrotron, Librarian, Hamburg, Germany
H. Ehrhardt, U. Kaiserslautern, Germany
A. A. Forster, Technischen, Universität Munchen, Germany
H. U. Gersch, Zfk Rossendorf, Dresden, Germany
Gesellschaft für Schwerionen-forschung mbH, Bibliothek, Darmstadt, Germany
K-O. Groeneveld, Universität Frankfurt, Germany
D. Habs, Max-Planck Inst. für Kernphysik, Heidelberg, Germany
J. W. Hammer, U. Stuttgart, Germany
H-J. Körner, Technische Universität München, Germany
W. Kühn, U. Giessen, Germany
H. G. Kümmel, Ruhr Universität Bochum, Germany
J. F. Last, U. Heidelberg, Germany
H. O. Lutz, Universitat Bielefeld, Germany
N. Marquardt, Ruhr-Universität Bochum, Germany
C. Mayer-Böricke, Kernforschungsanlage Jülich, Germany
T. Mayer-Kuckuk, Universität Bonn, Germany
U. B. Mosel, Universität Giessen, Germany
A. Müller-Arnke, Technischen Hochschule, Darmstadt, Germany
Munich, U. of, Physics Section Library, Garching, Germany
O. Osberghaus, Universität Freiburg, Germany
W. Potzel, Technischen, Universität München, Germany

A. Richter, Tech. Hochschule, Darmstadt, Germany
G. Rosner, Technische Universität München, Garching, Germany
D. Schneider, Hahn-Meitner-Inst., Berlin, Germany
O. W. B. Schult, KFA Jülich, Germany
P. Sperr, Hochschule d. Bundeswehr München, Neubiberg, Germany
J. Speth, Inst. für Kernphysik der KFA, Julich, Germany
U. Strohbusch, Inst. für Experimentalphysik Zyklotron, Hamburg, Germany
Technischen Universität München, Library, Physik Dept., Garching, Germany
D. von Ehrenstein, U. Bremen, Germany
S. Wagner, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
G. Anagnostatos, N.R.C. Demokritos, Athens, Greece
N. Gangas, U. of Ioannina, Greece
J. Cseh, Inst. Nuclear Research, Hungarian Ady. Sciences, Debrecen, Hungary
N. Anantaraman, VEC Lab., Calcutta, India
Bhabha Atomic Research Centre, Calcutta, India
M. R. Bhiday, U. Poona, India
S. Chakravarti, Jadavpur U., Calcutta, India
P. Chowdhury, Reactor Research Centre, Tamil Madu, India
M. Ismail, Bhabha Atomic Research Centre, Calcutta, India
Kashmir, U. of, Post Graduate Dept. of Physics, India
G. K. Mehta, Indian Inst. of Technology, Kanpur, India
N. Nath, Kurukshetra U., India
S. P. Pandya, Physical Research Lab., Ahmedabad, India
N. G. Puttaswamy, Bangalore U., India
I. Ramarao, Tata Inst. of Fundamental Research, Bombay, India
A. P. Shukla, Indian Inst. of Technology, Kanpur, India
P. C. Sood, Banaras Hindu U., Varanasi, India
Indonesia, U. of, Jakarta, Indonesia
Mosul, U. of, Dept. of Physics, Iraq
J. Alster, Tel Aviv U., Ramat-Aviv, Israel
D. Ashery, Tel Aviv U., Ramat-Aviv, Israel
A. E. Blaugrund, Weizmann Inst. of Science, Rehovot, Israel
Y. Eisen, SOREQ Nuclear Center, Yavne, Israel
Hebrew U., Theoretical Physics Dept., Jerusalem, Israel
D. Maor, Technion, Haifa, Israel
A. Marinov, Hebrew U., Jerusalem, Israel
M. Moinester, Tel Aviv U., Israel
Negev, U. of, Physics Preprint Library, Beer-Sheva, Israel
M. Paul, Hebrew U., Jerusalem, Israel
I. Plesser, Weizmann Inst. of Science, Rehovot, Israel
B. Rosner, Technion - Israel Inst. of Technology, Haifa, Israel
A. Weinreb, Hebrew U., Jerusalem, Israel
Weizmann Inst. of Science, Physics Library, Rehovot, Israel
C. Coceva, C.N.E.N., Bologna, Italy
Istituto di Fisica, Preprint Librarian, Torino, Italy
Istituto di Fisica dell Universita, Catania, Italy
Istituto di Fisica Sperimentale, Preprint Library, Torino, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Italy
Istituto Superiore di Sanita, Laboratorio della Radiazioni, Rome, Italy
M. Mando, Phys. Inst. of the University, Firenze, Italy
C. Signorini, Instituto di Fisica, Padova, Italy
Y. Abe, Kyoto U., Japan
F. Fujimoto, U. Tokyo, Japan
K. Hiida, U. Tokyo, Japan

K. Iwatani, Hiroshima U., Japan
K. Katori, U. of Tsukuba, Ibaraki, Japan
M. Kawai, Kyushu U., Fukuoka, Japan
H. Kudo, U. Tsukuba, Ibaraki, Japan
K. Kubodera, Sophia U., Tokyo, Japan
S. M. Lee, U. of Tsukuba, Ibaraki, Japan
Nagoya U., Dept. of Physics, Preprint Center, Japan
H. Narumi, Hiroshima U., Japan
H. Ohnuma, Tokyo Inst. Technology, Japan
Cyclotron Laboratory, RIKEN, Saitama, Japan
S. Takeuchi, Japan Atomic Energy Research Institute, Tokai, Japan
Tohoku U., Dept. of Nuclear Engineering, Sendai, Japan
Tokyo, U. of, High Energy Physics Lab., Japan
Tokyo, U. of, Inst. for Nuclear Study, Lib., Japan
Tokyo, U. of, Meson Science Lab., Japan
Korea Advanced Energy Research Inst., Technical Information Div., Seoul, Korea
Korea U., Physics Dept., Seoul, Korea
Instituto de Fisica, Theoretical Physics Grp., Preprint Lib., Mexico City, Mexico
Instituto Politecnico Nacional, Physics Dept. Lib., Mexico City, Mexico
J. Blok, Free U., Amsterdam, The Netherlands
H. de Waard, Rijksuniversiteit, Groningen, The Netherlands
Free University, Bibliotheek, Amsterdam, The Netherlands
P. F. A. Goudsmit, Inst. for Nuclear Physics Research, Amsterdam, The Netherlands
G. Jonkers, Free Univ., Amsterdam, The Netherlands
Koninklijke Nederlandse Akademie van Wetenschappen, Library, Amsterdam, The Netherlands
R. H. Siemssen, U. Groningen, The Netherlands
G. van Middelkoop, Vrije Universiteit, Amsterdam, The Netherlands
A. Vermeer, U. Utrecht, The Netherlands
A. Poletti, U. Auckland, New Zealand
A. Amusa, U. of Ife, Ile-Ofe, Nigeria
J. F. Williams, Queens U., Belfast, Northern Ireland
Pakistan Inst. of Nuclear Science and Technology, Rawalpindi, Pakistan
Quaid-e-Azam U., Dept. of Physics, Islamabad, Pakistan
Q. O. Navarro, Philippine Atomic Energy Commission, Quezon City, Philippines
J. Kuzminski, Inst. of Physics, Katowice, Poland
W. Zych, Warsaw Technical U., Poland
Lab. de Fisica de Engenharia Nucleares, Sacavem, Portugal
Institute for Physics and Nuclear Eng., Bucharest, Romania
Timisoara, U. of, Library, Romania
D. Branford, U. Edinburgh, Scotland
D. H. Pringle, Nuclear Enterprises Ltd., Edinburgh, Scotland
E. Barnard, Atomic Energy Board, Pretoria, South Africa
F. D. Brooks, U. Cape Town, South Africa
W. R. McMurray, Southern Universities Nuclear Inst., Faure, South Africa
D. W. Mingay, Atomic Energy Board, Pretoria, South Africa
D. Reitmann, National Accelerator Center, Stellenbosch, South Africa
J. P. F. Sellschop, U. of the Witwatersrand, Johannesburg, South Africa
O. Almen, Chalmers U. of Technology, Gothenburg, Sweden
I. Bergstrom, Nobelinstitut für Fysik, Stockholm, Sweden
M. Braun, Research Inst. of Physics, Stockholm, Sweden
N. Ryde, Chalmers U. of Technology, Gothenburg, Sweden

Tandem Accelerator Lab., Uppsala, Sweden
E. Ungricht, Inst. für Mittelenergie-Physik, Villigen, Switzerland
S. Ketudat, Chulalongkorn U., Bangkok, Thailand
Diyarbakir U., D. U. Fen Fakultesi, Turkey
A. Saplakoglu, Ankara Nuclear Research and Training Center, Ankara, Turkey
A. F. Tulinox, Moscow State University, U.S.S.R.
A. J. Kálnay, IVIC, Physics Section, Caracas, Venezuela
Venezuela, Universidad Central de, Physics Dept., Caracas, Venezuela