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PHYSICS DIVISION ANNUAL REVIEW

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Donald S. Gemmell
Division Director

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<u>Preceding Annual Reviews</u>

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FOREWORD

A major highlight of the Physics Division's activities over the past year was the acceleration of the first heavy-ion beams through ATLAS using the newly completed Phase 1 of the positive-ion injector. This took place in February 1989, when an Ar^{12+} beam from the ECR ion source was accelerated to 172 MeV and used in conjunction with the BGO facility for a measurement on high-spin states of ^{158}Er produced through the 4n reaction on a ^{122}Sn target. After this modest but significant beginning, the new injector has been refined and continually improved. The entire upgrade project for ATLAS is on schedule and due for completion early in FY91.

The ATLAS upgrade is also known as the "uranium upgrade" since it is designed to permit the acceleration of ion beams spanning the mass range of the whole periodic table. The capabilities of the ECR ion source for producing uranium-ion beams were demonstrated early in 1989. Using UF_6 and an oxygen support gas, the ECR source produced prolific beams of multiply charged uranium ions. The charge states and ion currents were well in excess of those required to meet the specifications of the upgraded ATLAS. An atomic physics experiment studying transitions in a lower charge-state ion (U^{5+}) demonstrated that the ECR source is capable of running a uranium-ion beam for protracted periods (in this case 12 hours) without the need for source adjustments. The experiment ran for several hours unattended and the beam current of 100 pnA remained essentially constant. All of these developments bode well for the capabilities of ATLAS when the upgrade is complete.

On the afternoon of June 29, 1988 the Physics Division held an event celebrating the "Tenth Anniversary of the First Heavy-ion Acceleration with a Superconducting Linac". The event began with an assembly in a large tent pitched near the ATLAS building. Argonne staff members, their spouses, representatives from DOE, the University of Chicago, congressional offices, and from other Laboratories gathered together in perfect weather conditions. After welcoming and opening remarks from Laboratory management, Lowell Bollinger gave a short talk on "How it all happened". This was followed by talks from Walter Henning (now at GSI) on "How we used it right away" and John Schiffer on "How we might use it in the future". There were then tours of ATLAS, refreshments, a buffet, and a social gathering accompanied by music provided by Cary Davids' jazz quartet.

Other ATLAS-related highlights include a very productive program of measurements of high-spin structures in a variety of nuclei using the BGO gamma-ray facility. This facility which was completed in 1987, now accounts for approximately 40% of the beam time used at ATLAS. Proceeding in close collaboration with our nuclear theory group, the ATLAS experiments have been highly successful in discovering and characterizing new regions of superdeformation.

A collaborative team involving scientists from Florida State University, Michigan State University, Princeton University, the University of Washington, Yale University, and Argonne National Laboratory has developed and submitted a proposal for an ATLAS positron experiment, "APEX". The proposal was favorably reviewed during the first half of 1989 and we look forward to obtaining funding to proceed with this exciting application of the uranium beams expected from

ATLAS early in 1991. The aim of this experiment is to confirm the anomalous positron peaks observed at GSI and to make systematic studies to try to determine their origin. The large solid angle of the solenoidal spectrometer being proposed, together with the CW characteristics of the ATLAS beams is expected to provide a high rate of data acquisition in these experiments which have hitherto suffered from low counting rates and poor statistical accuracy.

A substantial effort has been made over the past year by Physics Division staff in connection with the proposed GAMMASPHERE facility. This device represents the next generation of large gamma-ray detector arrays and will be especially suited for the study of high-spin states in nuclei. Argonne has participated vigorously in the nation-wide effort to develop a proposal for GAMMASPHERE. This proposal has been favorably reviewed both scientifically and technically. We expect to play a major role in the design, construction, and use of the facility.

Construction of the Fragment Mass Analyzer (FMA) is now well advanced. This device is expected to be completed early in 1990, and should significantly expand the experimental capabilities at ATLAS. It will be housed in the new ATLAS target room (Area IV) which has recently been completed. Another major piece of equipment that we hope to install in Area IV is that for the APEX experiment.

In Medium Energy Physics our collaboration with scientists at Novosibirsk is progressing successfully. We are engaged in measurements at the VEPP-3 storage ring to measure polarization in e-D scattering. The work is proceeding in three phases corresponding to progressively denser targets of polarized deuterons. Phases I and II employ conventional atomic-beam sources. Phase III, scheduled to be implemented next year, will employ an ANL development, viz. a deuteron target polarized through a spin-exchange mechanism with an alkali vapor which in turn is polarized by laser pumping.

Our staff is involved in Experiment E665 at Fermi Lab. This study of deep inelastic muon scattering at high energies is being conducted by a large multi-national collaboration. Argonne's contribution represents the nuclear physics interest in an otherwise wholly high-energy physics effort. The experiment addresses a central issue in nuclear physics, the modification of the structure of the nucleon in nuclear matter.

Argonne staff members are heavily involved in preparations for the experimental program at CEBAF. Our staff are spokespersons on 7 Letters-of-intent that have been submitted to CEBAF and we are collaborators on one further letter-of-intent. We have proposed to build a short-orbit spectrometer for experiments involving the production of short-lived hadrons, and we are participating in the design of the 6-GeV "Core" spectrometer for Hall C. In addition, several of our staff are involved in advisory capacities at CEBAF.

In May 1989, the Physics Division ran a symposium on the occasion of the "40th Anniversary of the Nuclear Shell Model". There were twenty invited talks, six contributed talks, and a poster session with sixteen papers. Approximately 130 people attended the meeting. Argonne was an appropriate site for this symposium since the modern nuclear shell model was conceived in 1949 by Maria Goeppert Mayer, who was then on our staff, and independently in Germany by J. Hans D. Jensen, Otto Haxel, and Hans E. Suess. Later, many workers at Argonne played an important role in the development and application of the shell model. During the meeting, Laboratory Director Alan Schriesheim dedicated a plaque honoring Maria Goeppert Mayer at the entrance to the physics building and announced a new initiative, the Maria Goeppert Mayer Distinguised Scholar Program, with the intention of attracting outstanding women scientists and engineers to the Laboratory.

Our Atomic Physics group has been quick to avail itself of the "Window of opportunity" for atomic physics studies using the ATLAS ECR ion source. The unique feature that the source is located on a 350-kV high-voltage platform opens up experimental possibilities not elsewhere available.

Now that funding for the Advanced Photon Source (APS) at Argonne seems assured, our staff are developing ideas for the exploitation of this powerful new device for studies in atomic physics.

During the past year, the Division had the pleasure of hosting Professor Peter Sigmund from Odense University, Denmark. Dr. Sigmund, a theorist well known for his work in atomic collisions, spent a year with us as an Argonne Fellow. In addition to his many scientific contributions, Peter added significantly to the cultural environment at Argonne through his musical abilities. A special event of the past year was the concert arranged by Peter Sigmund (Piano) and Walter Kutschera (Violin) in the Argonne Lodge.

D. S. Gemmell

Donald S. Gemmell
Director, Physics Division

August 1989

THIS DOCUMENT IS DIVIDED INTO THE FOLLOWING MAIN SECTIONS:

NUCLEAR PHYSICS RESEARCH

ATOMIC AND MOLECULAR PHYSICS RESEARCH

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I. RESEARCH AT ATLAS

The heavy-ion research program of the Argonne Physics Division is conducted mainly at ATLAS, the Argonne Tandem-Linac Accelerator System. Allocation of beam time is based on the advice of a Program Advisory Committee. Activities of the staff are divided among: (a) on-going research, (b) construction and improvement of apparatus at ATLAS, and (c) planning, designing, prototype testing, and construction of equipment to exploit the new beams provided by an ATLAS upgraded with the positive ion injector. Users from outside Argonne participate in over 70% of the experiments at ATLAS.

The research program covers a broad range of topics related to the properties of rapidly-rotating nuclei, the interaction dynamics of heavy-ion collisions and the mutual influence of nuclear properties and the dynamics of reactions. Other programs include accelerator mass spectrometry, study of the properties of a condensed state of cooled ions, and nuclear astrophysics. With the new capabilities of the upgraded ATLAS we have undertaken extensive preparations to investigate the origin of the sharp e^+e^- coincidence peaks seen at GSI. A Fragment Mass Analyzer now under construction will allow us to initiate studies of exotic nuclei.

The structure of nuclei at very high spin reflects the interesting interplay of classical and quantal aspects. One striking consequence is the occurrence at high spin of superdeformed prolate shapes with ~ 2:1 axis ratio. In ^{151}Dy and ^{191}Hg we have observed long cascades of γ transitions with energies characteristic of rotational bands associated with these shapes. The relatively strong population of these discrete superdeformed bands is surprising. From studies of the precursor γ transitions we have determined that the initial population of the superdeformed shapes is cold, which partially accounts for the confinement in the secondary superdeformed minimum. In the transitional $N \simeq 88$ nuclei we have observed clear signatures of structural changes with increasing excitation energy and spin, reflecting the persistence of shell effects and order up to 5 MeV above the yrast line. New examples of another type of exotic nuclear shape, octupole deformation, have been found in both the actinide and Ba-Ce region, the latter from γ-γ coincidences in ^{252}Cf fission fragments. These studies have profited from fruitful collaborations with groups from Notre Dame, Purdue, I.N.E.L., Manchester, Montreal, Giessen and Heidelberg, as well as interactions with the Argonne theory group.

Nucleon exchange is the elementary transfer mode in heavy-ion reactions. Complex processes such as deep-inelastic scattering and fusion represent the limiting case in which a large number of nucleons are exchanged between the reaction partners. Thus, it is important to understand the process of quasielastic few-nucleon transfer reactions, both its detailed properties, such as the dependence on projectile or target mass and Q-value (binding energy), and its influence on other processes such as sub-barrier fusion. The quasielastic transfer cross sections in ^{100}Mo + Ni reactions have been measured with the heaviest beams used so far at ATLAS for reaction studies. The cross sections were surprising both because they were smaller than predicted on the basis of the systematics developed at Argonne, and because this did not correlate with the large sub-barrier enhancement of fusion previously reported in the same reaction. In several cases, the probability for neutron transfer as a function of the distance of closest approach was in accord with theory. However, there were examples of reactions with deformed nuclei where this was not so -- giving rise to a so-called slope anomaly. New neutron-rich nuclei, e.g. ^{72}Ni, were produced in experiments utilizing deep-inelastic collisions, where more nucleons were transferred. An interesting investigation, representing the interface between nuclear and atomic physics, was successfully conducted to study the atomic charge-state dependence of nuclear lifetimes in ^{57}Fe ions.

Another major area of research concerns processes where substantial rearrangement of the nucleons of the reaction partners takes place, i.e., fusion and fission-like processes. A new aspect of these studies is the use of coincidences between charged particles and γ rays, detected with high-resolution Ge detectors at the Argonne-Notre Dame γ facility. In fission of ^{56}Ni we have found unexpected indications of octupole-deformed shapes formed at scission and persisting to low-lying discrete states of the fragments. Another promising application of this technique was in studies of incomplete fusion in the ^{12}C + ^{160}Gd reaction, where evidence was found for pre-equilibrium emission of α particles with near beam velocity. The γ-ray angular distributions and multiplicities were markedly different in complete and incomplete fusion. Whereas in lighter systems the high relative velocities of projectile and target leads to incomplete fusion, in very heavy systems the large Coulomb barrier is an impediment to fusion. Instead a large net transfer of mass from the heavy to the light reaction partner takes place in quasifission reactions. The time scale in this quasifission process has been measured and supports the notion that the dissipation mechanism is temperature-independent, suggesting long nucleon mean-free paths.

Our program on accelerator mass spectrometry (AMS) has focussed on exploring the possibility of radiocalcium dating of fossil bones through measurements of the concentration of ^{41}Ca. If successful, this method has the potential to extend the time scale of radioisotope dating to 0.1-1 x 10^6 y, about an order-of-magnitude earlier than possible with radiocarbon dating. A large increase in the intensity of Ca-beams from a new sputter source has resulted in successful detection of ^{41}Ca from natural samples without the need for the pre-enrichment, which was hitherto necessary.

In preparation for experiments utilizing the U beams which will be available in 1991, we have devoted substantial effort, in collaboration with several university groups, towards the design of a second-generation apparatus for measurements of the interesting e^+e^- coincidence peaks seen in collisions between very heavy ions at GSI. A proposal for an apparatus capable of specifying the initial momenta of the positrons and electrons, as well as obtaining a counting efficiency of at least an order-of-magnitude larger than in the GSI experiments has been submitted to DOE..

Other areas of research include calculations of the properties of a condensed crystalline structure in cooled ions contained in traps or intense heavy-ion beams circulating in storage rings. Vibrational and sheer modes of these structures have been investigated, as have the effects of the periodic focussing which would be encountered by the ions in a ring. Predictions of layered structures of cooled trapped atoms have recently been observed in experiments performed elsewhere.

ATLAS is being applied to current issues in stellar nucleosynthesis: a novel method making use of the good beam emittance has been developed to extract the γ width of an excited state in ^{14}O which is important in the hot CNO-cycle.

The detection system at ATLAS is continually being improved. A major effort is the construction of a Fragment Mass Analyzer (FMA). Major components have been ordered, tests have been conducted on the power supplies for the electrostatic deflectors. A new extension has been added to the experimental area to house the FMA, the beam-transport system has been designed and is presently being built, as is the mechanical support for the instrument. In designing the spectrometer system for the positron experiments, energy- and time-resolution tests of Si pin diodes were conducted with encouraging results. In preparation for GAMMASPHERE, a National Gamma Ray Facility, we have undertaken design studies of prototype Ge and BGO detectors and have placed orders for both; evaluation of the prototypes will be performed at Argonne. The properties of our facility, in particular the availability of a complete range of beams, excellent beam timing, and the relative ease of coupling with the FMA (essential for study of very weak channels), make ATLAS the ideal accelerator for providing beams to GAMMASPHERE.

A. QUASIELASTIC PROCESSES AND STRONGLY-DAMPED COLLISIONS

The study of quasi- and deep-inelastic processes again constitutes a major part of the ATLAS experimental program. The main goal of these studies is to improve our understanding of more complex nuclear reactions by studying these processes at energies in the vicinity of the interaction barrier. At these low energies the reactions are dominated by the Coulomb force and in many cases reliable predictions about the strength for the interaction can be obtained using existing theoretical models. By increasing the bombarding energy the complexity of the interaction increases and the failure of various theoretical models can be studied in detail. One example for this behavior is the failure of one-dimensional barrier-penetration calculations to describe the low-energy fusion cross sections measured for heavy-ion-induced reactions. Quasi-elastic reactions (inelastic scattering and few-nucleon transfers) have been found to be responsible for the discrepancy between theory and experiment, and improved coupled-channel calculations, including these reaction channels, are now in good agreement with the experimental data. A knowledge of the strength of these quasielastic processes is a crucial ingredient in all these calculations. With the availability of heavier beams from ATLAS we have extended our studies of quasielastic processes to heavier systems. In particular for the system ^{64}Ni + ^{100}Mo a large subbarrier fusion enhancement has been observed. Surprisingly the measurements of the quasielastic reactions for this system using a ^{100}Mo beam from the ATLAS accelerator showed unexpectedly small transfer cross sections. This result indicates that inelastic scattering alone must have a larger influence on subbarrier fusion than previously assumed.

The study of processes occurring at large distances between the two interacting nuclei produced some unexpected results. The energy dependence of the one- and two-neutron transfer reactions measured at subbarrier energies using the Daresbury Recoil Mass Separator in the systems ^{58}Ni + Sm was found to be in agreement with theoretical predictions only for the spherical ^{144}Sm. The falloff of the one-neutron transfer cross section with decreasing energy for ^{148,150,152,154}Sm, on the other hand, was much smaller than expected on the basis of the theoretical calculations. A similar strong system dependence of the cross sections at large distances was found for the two-neutron transfers in a large number of systems measured at ATLAS. The reasons for these discrepancies are not understood at the moment but they point to a large nuclear-structure dependence in these reactions.

The model for understanding the total transfer strength in one-neutron transfer reactions involving medium-mass projectiles and heavy targets has been extended to two-neutron transfer reactions and again good agreement with the semiclassical picture has been obtained. There are, however, some reaction systems involving A = 100 nuclei where discrepancies from this simple picture have been observed. A study of these deviations and an extension of the semiclassical model to charge transfer is presently in progress.

The study of the energy dependence for inelastic scattering and transfer reactions for Si + ^{208}Pb was extended to bombarding energies of 15 MeV/u. The system ^{28}Si + ^{208}Pb has now been studied from energies close to the Coulomb barrier up to 420 MeV and a good description of the low-lying collective states in Si and Pb has been obtained within the framework of coupled-channels calculations. For the case of ^{30}Si + ^{208}Pb the intrinsic quadrupole moments of the first two excited 2^+ states in ^{30}Si could be determined.

Other experiments involved the study of the neutron-number dependence of deep-inelastic processes for the system ^{64}Ni + ^{112,118,124}Sn and the search for prolonged interaction times in transfer reactions involving systems where superdeformed shapes had been observed. The study of deep-inelastic reactions at energies close to the barrier was continued with the system ^{64}Ni + ^{92}Zr. Similar to our previous studies with Ni + Sn, deep-inelastic processes were found to be of similar strength as compound nucleus formation at energies close to the barrier. Deep-inelastic reactions were also used to study the production of extremely neutron-rich nuclei in the collisions of ^{76}Ge + ^{186}W. For the Ni-isotopes the production of ^{72}Ni was observed in these reactions.

The analysis of an experiment of interest to both nuclear and atomic physics has been completed. In this study the charge-state dependence of internal conversion has been studied for the first time in highly-stripped ^{57}Fe ions. It was found that the lifetime of a $^{57}Fe^{25+}$ ion is actually shorter than the one for $^{57}Fe^{24+}$. In addition, the charge-state dependence of the fluorescence yield for highly-stripped Fe ions could be determined. This type of experiment can be extended to heavier ions and various implications in the fields of nuclear and atomic physics might arise from these studies.

a. Quasielastic Reactions of ^{30}Si on ^{208}Pb (D. G. Kovar, K. E. Rehm, J. J. Kolata,* and R. J. Vojtech*)

Quasielastic processes (elastic and inelastic scattering and few-nucleon transfer) have been measured for the ^{30}Si + ^{208}Pb system at $E_{lab}(^{30}Si)$ = 220 MeV, using the split-pole magnetic spectrometer and its associated focal-plane detector system. Coupled-channels analysis of the elastic and inelastic scattering results in an excellent description of the experimental data which included, in addition to the elastic scattering, the angular distributions for the inelastic scattering to the ^{30}Si(2.23,2^+), ^{30}Si(3.50,2^+), ^{208}Pb(2.61,3^-),

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and $^{208}Pb(4.08, 2^+)$ states and the mutual excitation of the first-excited states of ^{30}Si and ^{208}Pb at E_x = 4.8 MeV. Angular distributions for these states together with the results from coupled channel calculations are shown in Fig. I-1. The static quadrupole moments of the first two 2^+ states in ^{30}Si are measured to be -9±4 e fm^2 and -4±9 e fm^2, respectively. The sign of the interference term for the transition between the two states is unambiguously determined to be negative, corresponding to destructive interference. DWBA calculations using the optical-model potential deduced from the coupled-channel analysis of the elastic-scattering data were able to reproduce the total yield and the excitation-energy distribution for the $^{208}Pb(^{30}Si,^{31}Si)^{207}Pb$ reaction at the grazing angle. However, the calculated angular distribution is characteristically too narrow and markedly underpredicts the cross sections at angles forward of the grazing peak. The cross section for quasielastic processes, including inelastic scattering, accounts for 25% of the total reaction cross section. A paper has been submitted for publication.

b. Quasielastic Reactions of ^{28}Si with ^{208}Pb (K. E. Rehm, D. G. Kovar, S. Dixit,* J. J. Kolata,* R. A. Kryger,* A. Morsad,* R. Tighe,* X. J. Kong,* W. K. Chung,* and R. J. Vojtech*)

Data were collected for the system ^{28}Si + ^{208}Pb at beam energies of 280 MeV and 420 MeV. We have measured quasielastic reaction products (elastic and inelastic scattering and few-nucleon transfer) over the angular range E_{lab} = 5° - 40° with the split-pole spectrograph. This is a continuation of a program to study quasielastic reactions of ^{28}Si + ^{208}Pb from the Coulomb barrier to the highest ATLAS energies. The data are presently being analyzed at the Nuclear Structure Laboratory of the University of Notre Dame. To date, the analysis for elastic and inelastic scattering at 280 MeV has been completed and good agreement with Ptolemy coupled-channels calculations for all measurable states has been found. The optical-model potential previously obtained from the analysis of the 6- and 8-MeV-per-nucleon data was used in this calculation. Work has begun on the analysis of the 420-MeV data, and some preliminary cross sections have been obtained. We expect that all data will be analyzed and a manuscript describing the results will be prepared by the end of the coming summer.

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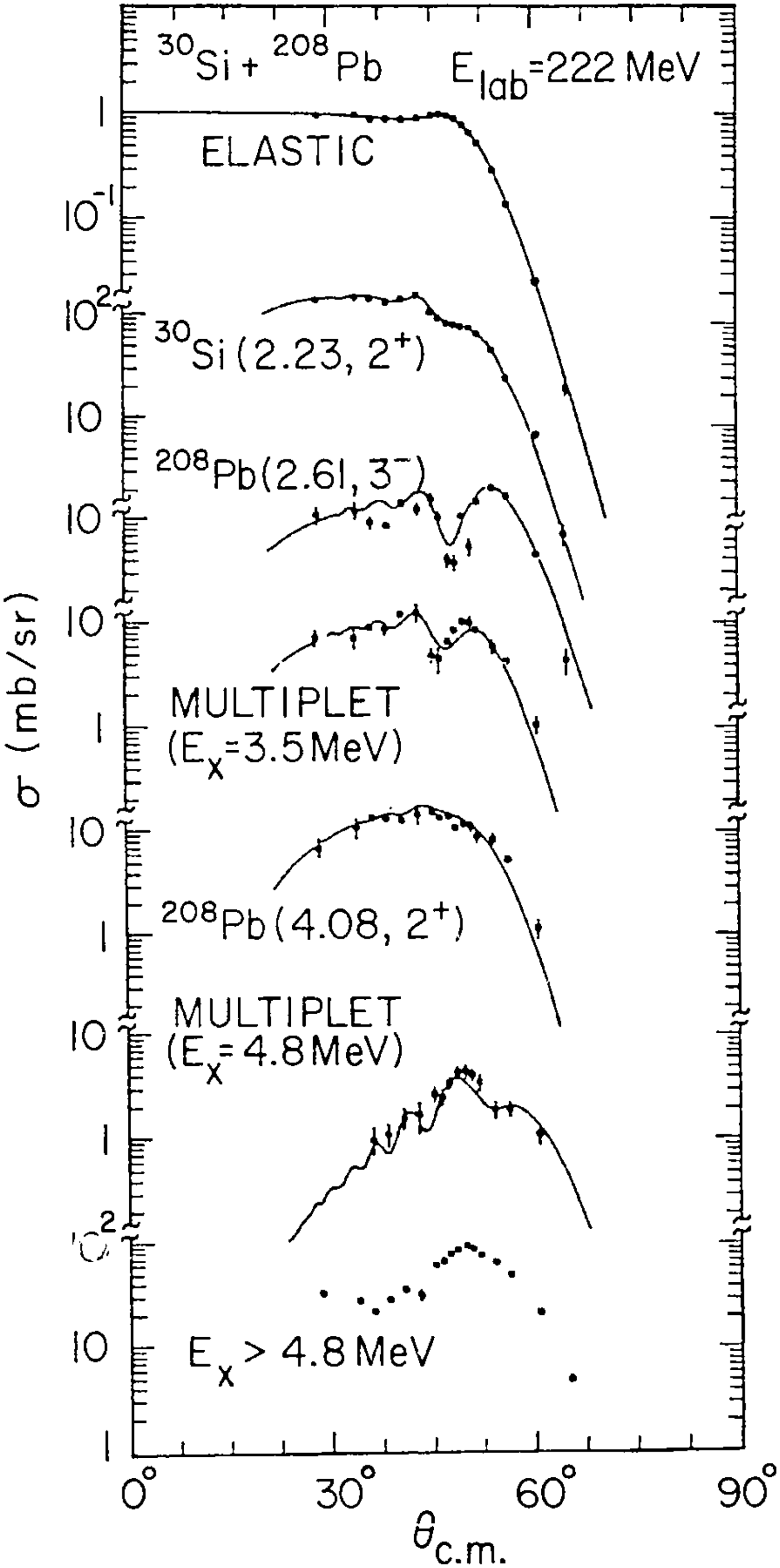

Fig. I-1. Angular distributions for elastic scattering and inelastic excitation of low-lying states in ^{208}Pb and ^{30}Si measured at E^{lab} = 222 MeV. The solid lines are the results of coupled channel calculations.

c. Measurement of Reactions at Sub-Barrier Energies using a Recoil Mass Separator (R. R. Betts, P. M. Evans,* C. N. Pass,* A. E. Smith,* J. S. Lilley,† A. N. James,‡ and B. R. Fulton§)

This program utilizes the Recoil Mass Separator (RMS) at the Nuclear Structure Facility, Daresbury Laboratory to measure transfer reactions between heavy ions at energies close to and below their mutual interaction barrier. Our initial experiments involved studies of one-neutron transfer of ^{58}Ni + ^{A}Sn in both angles and coincidence with decay gamma rays. These data have been subject to an intensive analysis in terms of both semi-classical models of the transfer process and distorted-wave Born approximation calculations. The conclusion of this analysis is that the overall strength and energy dependence of the observed cross sections is well understood although the detailed population of individual final states observed from the gamma-ray coincidence data show discrepancies. This appears as a deficiency in the observed cross sections in the target-like nucleus when compared to the DW predictions. Experimentally, the missing cross section is found in final states of a structure $(n\ell j)_{\nu}^{-1} \times 2^{+}$ which is precluded from excitation in a direct one-step nucleon transfer. The description of these data is being sought in coupled-channels calculations of inelastic scattering and transfer. These results will be published shortly.

In contrast to the generally good understanding of the ^{58}Ni + Sn results, similar data for ^{58}Ni + Sm show distinct anomalies. Measurements have been made for the even stable Sm isotopes which range from the closed-shell ^{144}Sm to well-deformed prolate ^{154}Sm. The ^{144}Sm data for both one- and two-neutron transfer are well described by both semi-classical and DW calculations, as was the case for ^{58}Ni + Sn. The one-neutron transfer on all the other targets, ^{148,150,152,154}Sm all show a much smaller falloff with decreasing energy than expected on the basis of the calculation. The two-neutron transfer, however, appears normal. This is the first time that the so-called "slope anomaly" has been observed in one-neutron transfer. Its origin is not understood at present.

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We hypothesize that the anomaly is a channel coupling effect which results from the rather "cold" population of final states in the one-neutron transfer as opposed to the more highly-excited states favored by the reaction dynamics in the two-neutron transfer. These ideas will be resolved in a number of experiments to be carried out at Daresbury and Argonne this year.

d. Search for Prolonged Interaction Times in Transfer Reactions at the Barrier (S. J. Sanders, B. B. Back, R. R. Betts, D. Henderson, R. V. F. Janssens, T. L. Khoo, E. F. Moore, K. E. Rehm, and F. L. H. Wolfs)

In continuation of our previous experiments to investigate whether heavy-ion molecular behavior exists in heavier systems, we have studied the system $^{64}Ni + ^{92}Zr$. If reaction channels couple to superdeformed nuclear shapes, a delay in the interaction time might occur which would manifest itself in an increased cross section for this particular channel at forward angles. Although no clear evidence for a cross section enhancement has been found for the system $^{48}Ti + ^{104}Ru$, populating the compound nucleus ^{152}Dy (on which a short report has been published) we have studied the Ni + Zr system leading to the compound nucleus ^{156}Er, where indications for superdeformation have previously been observed. The experiment was performed in the split-pole spectrograph with the new focal-plane counter as detection system. To obtain a redundant time-of-flight measurement for background reduction, a channel-plate start detector at the entrance of the spectrometer was installed. In addition, the vacuum in the magnet chamber was improved to reduce the effects of charge-exchange processes with the residual gas which can simulate transfer processes at extreme forward angles. The data are presently being analyzed. In a preliminary on-line analysis no indication for an enhancement in the one-neutron transfer reaction $^{92}Zr(^{64}Ni,^{63}Ni)^{93}Zr$ could be observed. A paper on this work has been published.

e. Neutron Transfer Reactions in the Ni + Mo System (K. E. Rehm, B. Glagola, W. Kutschera, S. Sanders, T. F. Wang, F. L. H. Wolfs, and H.-J. Körner)

The large subbarrier fusion cross sections observed in the Ni + Ni systems have been explained by the coupling effects of quasielastic channels (inelastic scattering and transfer reactions) which reduce the fusion barrier considerably at low bombarding energies. Recently fusion cross sections measured in the system $^{64}Ni + ^{100}Mo$ again showed a large subbarrier fusion enhancement which could not be explained by the coupling effect of inelastic channels alone. We have therefore measured the strength of the transfer processes at energies close to the barrier. The experiments were done in inverse reaction kinematics with $^{92,100}Mo$ beams bombarding $^{58,64}Ni$ targets.

With this technique, even at low incident energies energetic Ni recoil particles are produced at forward angles, which greatly simplifies the particle identification. The experiments were performed at the split-pole spectrograph with the new detector in its focal plane. The analysis of the ^{100}Mo + Ni experiments is completed, while the analysis for the experiment with a ^{92}Mo beam is still in progress. The cross sections observed for these reactions are found to be surprisingly small and probably cannot be responsible for the large fusion enhancement. Thus other reaction modes might have to be considered for the coupling process. In addition the small transfer cross sections observed in this mass region are interesting since they indicate that contrary to other target nuclei (Sn, Sm, Pb, Th...), neutron transfer is not a strong reaction channel for Ni-induced reactions on mass-100 nuclei.

f. Systematics of Multi-Neutron Transfer Cross Sections in Heavy Systems
(K. E. Rehm, D. G. Kovar, W. Kutschera, J. L. Yntema, and A. van den Berg*)

The experimental angle- and energy-integrated cross sections for one-neutron transfer reactions induced by medium-weight projectiles, which were measured for a large number of systems during the last few years, follow a systematic behavior, which can be understood in a simple semiclassical model that is based on the Q-matching picture. We have analyzed our data for two- and three-neutron transfers along similar lines. The results are shown in Fig. I-2. As can be seen, reduced (i.e. binding-energy corrected) two-neutron transfer cross sections for a variety of systems ranging from ^{58}Ni + ^{64}Ni to ^{58}Ni + ^{232}Th follow the same systematics as observed in the one-neutron transfer reactions[1] but with a transfer strength which is smaller by about a factor of 5. The only case where a full angular distribution for the 3-n transfer has been measured (^{48}Ti + ^{208}Pb) is again smaller than the 2-n transfer by another factor of 5. No particular enhancement for the 2-n transfer involving Sn nuclei was observed.

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*KVI Groningen, Groningen, The Netherlands.
[1]A. M. Van den Berg et al., Phys. Lett. 194B, 334 (1987).

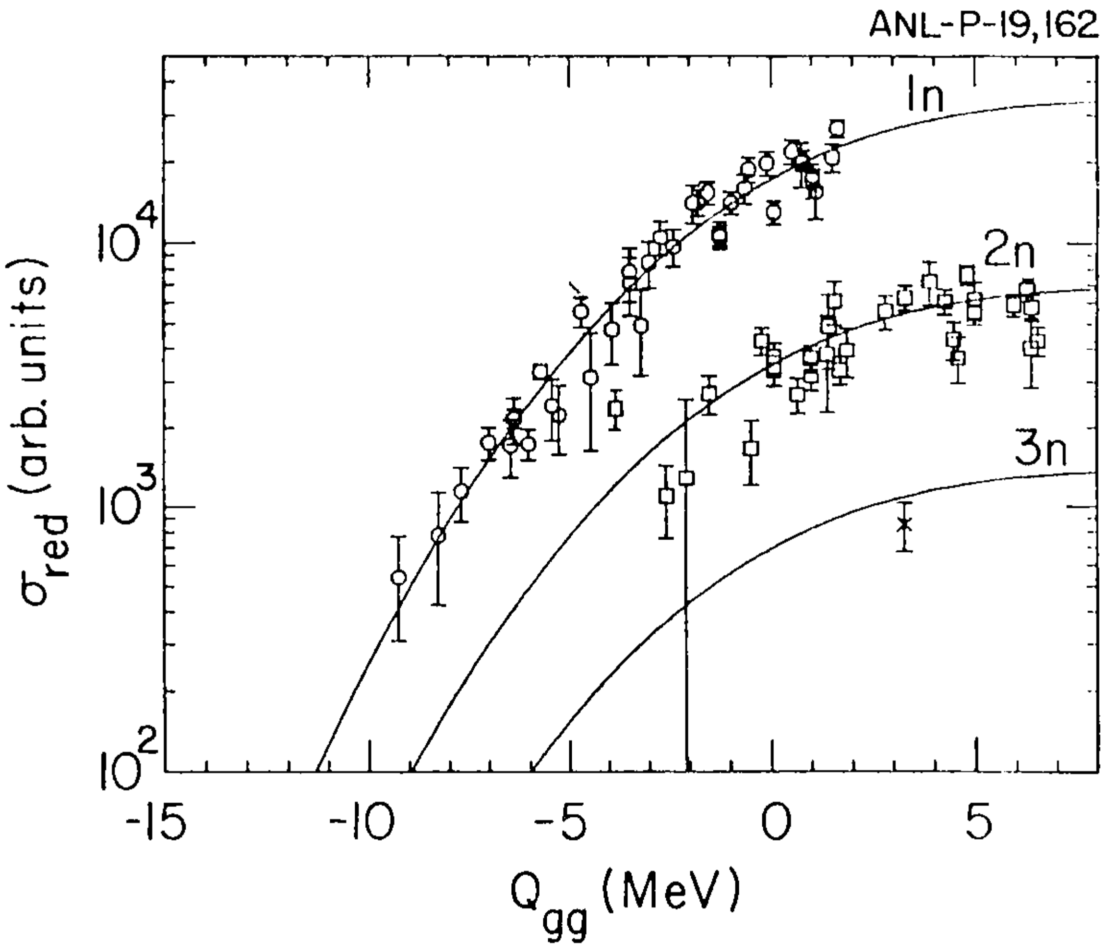

Fig. I-2. Binding energy corrected cross sections for one-, two- and three-neutron transfer reactions induced by medium-weight projectiles on heavy targets. The solid lines are obtained from a semiclassical model explained in Ref. 1.

g. One- and Two-Neutron Transfer Reactions on Deformed Nuclei (K. E. Rehm and F. L. H. Wolfs)

The shapes of the angular distributions for one- and two-neutron transfer reactions at forward angles sometimes show an unexpected behavior. If plotted vs. the distance of closest approach the falloff of the cross sections at large distances should be determined by the binding energy of the transferred neutron. While this is observed in general for the one-neutron transfer reactions, the two-neutron transfers show a more erratic behavior. While some systems (e.g. $^{58}Ni + ^{208}Pb$) show the expected (steep) falloff, other systems (in particular the ones involving deformed target nuclei) show a falloff which is similar to the one observed for one-neutron transfer reactions. We have measured the transfer cross sections for the system $^{58}Ni + ^{232}Th$ at E_{lab} = 500 MeV, using the split-pole spectrograph and the new focal-plane counter for a detection system. The data have been completely analyzed. Similar to our previous studies with the system $^{58}Ni + ^{154}Sm$ we obtain a slope for the one-neutron transfer reactions which is in agreement with the binding energy of the transferred neutron, whereas for the two-neutron transfer reaction again a disagreement with the expected slope is observed.

This phenomenon points at the influence of nuclear-structure effects for the case of two-neutron transfer reactions. We are presently analyzing all our previous data in order to look for a possible systematic behavior.

h. Study of Neutron-Rich Nuclei Produced in the $^{76}Ge + ^{186}W$ System (K. E. Rehm, C. Davids, R. V. F. Janssens, F. L. H. Wolfs, G.-E. Rathke, and H.-J. Körner)

We have studied the production of neutron-rich nuclei in the mass region between iron and germanium by heavy-ion-induced multinucleon transfer reactions. The motivation for these experiments was to learn about the reaction mechanism for these transfer reactions and to investigate the possibility for subsequent decay studies for these nuclei, which are of importance for a better understanding of the r-process in nucleosynthesis. The experiments were performed in the split-pole spectrograph equipped with the new focal-plane detector. This system allowed unique particle identification for all nuclei produced in this reaction. The system $^{76}Ge + ^{186}W$ was chosen, because previous studies at the mass separator facility at GSI showed that neutron-rich nuclei in this mass region can be produced by reactions involving Ge and Se beams on W targets. Due to the efficiency of the ion source these previous experiments could not obtain reliable values for the cross sections for all nuclei. We have studied the Ge + W system at incident energies of 430, 520 and 680 MeV. While at the lowest energy the transfer process is dominated by the few-neutron transfer reactions, a large spectrum of reaction products ranging from Ca-isotopes to Br-isotopes is observed at the highest energy. A preliminary analysis revealed that Ni isotopes up to ^{72}Ni (produced in a four-proton transfer reaction) could be observed. A full analysis of these experiments is in progress.

i. Deep-inelastic Scattering in Heavy-ion Reactions at Energies around the Coulomb Barrier (F. L. H. Wolfs)

A detailed study of the decomposition of the total reaction cross section for the Ni + Sn system at energies around the Coulomb barrier showed that in this energy region deep-inelastic scattering is an important reaction channel with yields similar to that of fusion. A recent measurement of the total reaction cross section and the fusion yields for the ^{64}Ni + ^{92}Zr system at energies between 1.05 and 1.30 times the Coulomb barrier also showed evidence for a significant strength of deep-inelastic scattering. At the lowest energies, only 50% of the reaction cross section (obtained from the measured elastic-plus-quasielastic-scattering angular distributions) is accounted for by fission and light-particle evaporation. This suggests that the strength of deep-inelastic scattering in the Ni + Zr system at energies close to the Coulomb barrier is similar to that previously measured in the Ni + Sn system.

The gamma decay of the deep-inelastic scattering products will be studied in an upcoming particle-gamma coincidence experiment using the BGO array.

j. Fission and Deep-Inelastic Scattering Yields for ^{64}Ni + ^{112,118,124}Sn at Energies Near the Coulomb Barrier (F. L. H. Wolfs, K. E. Rehm, J. P. Schiffer and T. F. Wang)

In continuation of our experiments with the systems ^{58}Ni + ^{112,124}Sn at energies close to the Coulomb barrier, where considerable contributions from deep-inelastic scattering were observed, ^{64}Ni + ^{112,118,124}Sn was studied in order to get information about the neutron number dependence of this process. Kinematic coincidence techniques with two large position-sensitive avalanche counters were used to obtain mass and Q-values for these reactions. The data are completely analyzed and a publication with the results is in preparation.

k. Charge-State Dependence of the Half-Life of the 14.4-keV State in ^{57}Fe
(I. Ahmad, B. G. Glagola, W. Kutschera, K. E. Rehm, J. P. Schiffer, T. F. Wang, W. Phillips,* D. Banes,* and W. Henning†)

We have measured the charge-state dependence of the half-life of the 14.4-keV state in ^{57}Fe in highly-stripped Fe-ions. The 14.4-keV level was populated by Coulomb excitation using a ^{57}Fe beam and an Au-target. The split-pole spectrograph with its new focal-plane detector was used for selecting the various charge states of the ^{57}Fe particles. Ions entering the magnetic field and undergoing no charge-changing process appear as a peak in the focal plane. Some ions in the 14.4-keV excited state will experience an internal conversion decay in the magnetic field. If the electron hole created in the decay is filled by X-ray emission the charge state in the Fe-ion will change by one unit. If the hole is filled by Auger-emission the charge state will increase by two units. Ions undergoing these charge-changing processes will be distributed in the focal plane between the undisturbed charge-state peaks. Some position spectra together with a Monte Carlo simulation using as input the actual geometry of the split-pole spectrograph is shown in Fig. I-3. Since Auger-emission complicates the picture we have so far concentrated on the analysis of the decay of the q = 24 and 25 states, where Auger emission is not possible. The half-life of the two-electron ion (q = 24) was measured to be 100 ± 5 ns, in good agreement with the value of the neutral atom of 98.1 ± 0.3 ns. For the one-electron ion (q = 25) a half-life of 79 ± 6 ns has been measured. The accuracy of these measurements can still be improved when larger beam intensities from the new positive-ion injector become available. An experiment to study the charge-changing processes for ^{83}Kr will be performed in the near future. A paper with the results for the one-and two-electron studies on ^{57}Fe has been published. The analysis for the other charge states, including results for the charge-state dependence of the fluorescence yields, is still in progress.

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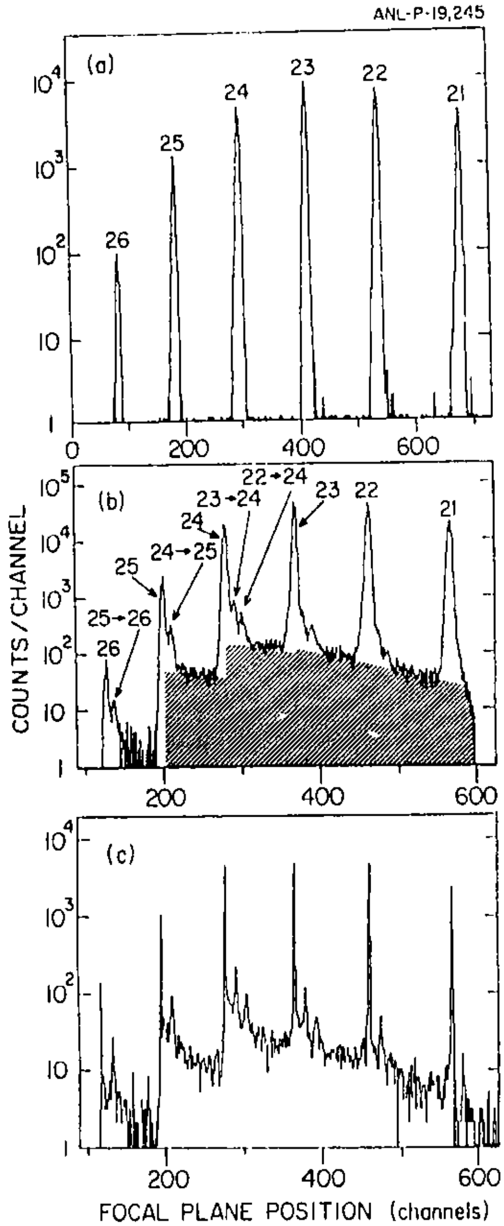

Fig. I-3. a) Position spectrum observed in the focal plane of the spectrometer for θ_L = 7.5° and a bombarding energy of 346 MeV. The strong peaks are labelled according to charge state q.
b) Position spectrum observed in the focal plane of the spectrometer for θ_L = 40°. The events between the strong peaks (see the cross-hatched area) are attributed to charge-changing processes after nuclear decay in the magnet. The small subsidiary peaks arise from charge changes (as labelled in the figure) in the nearly field-free gap between the two poles of the spectrograph.
c) Monte Carlo simulation of a position spectrum using the ion optical code RAYTRACE including charge-changing processes.

B. FUSION AND FISSION WITH HEAVY-ION BEAMS

The experimental studies of reactions in which substantial rearrangements between the interacting nuclei take place account for a major component of the ATLAS experimental program. Such reactions include complete fusion near the interaction barrier, fission or quasifission reactions in both heavy and light systems as well as incomplete fusion and projectile breakup reactions at higher beam energies.

Since fusion is such a substantial fraction of the total reaction cross section it is often important to measure the complete fusion cross section for certain systems in order to set the stage for other more specific studies. Thus a measurement of the subbarrier fusion of ^{58}Ni + ^{144,154}Sm was required to supplement detailed studies of neutron transfer reactions in these systems. Likewise, a measurement of the fission cross section in the ^{64}Ni + ^{92}Zr reaction was carried out to pin down the remaining uncertainties in interpreting an observed deficiency in the neutron emission from compound systems formed in this reaction.

The study of fission and fission-like reactions in heavy systems continues to be a substantial component of the ATLAS research program. Present efforts focus on the study of time scales for the quasifission process and their relation to the rate of mass transfer. These results show that the one-body dissipation mechanism dominates in this low-energy regime. Detailed studies of the spin-bearing modes of di-nuclear systems are underway. These include measurements of angular distributions at very forward angles as well as studies of the γ multiplicities as a function of fragment mass. Also the systematics of fragment mass distribution is being studied over a large range of the periodic table.

In contrast to heavy systems, fission and fission-like reactions account for only a small portion of the reaction strength in lighter nuclei (A < 100). In recent careful studies at Argonne it has, however, been shown that this component of fission exists in lighter systems and that the observed properties of the fission products may be explained in a satisfactory way by standard theoretical models. By combining the standard experimental techniques for detection and identification of the fission-fragments with the resolving power of the Notre Dame-ANL CSG-BGO array for γ detection, it has been shown that the phase space of the final fragments is not populated statistically. There appears to be a strong preference for the fragments to emerge from the reaction in an octupole shape, which probably reflects the shape at the point of scission.

The addition of γ-ray measurements has also advanced the study of incomplete fusion reactions by helping identify the final evaporation residues for which the velocity was measured by time of flight. In a recent study of the ^{12}C + ^{160}Gd reaction it was observed that γ rays emitted from the evaporation residues are most likely associated with fusion of a ^{8}Be projectile with the ^{160}Gd target nucleus. This leads to the conclusion that initially an α particle was lost from the projectile with the remaining fraction fusing with the ^{160}Gd target nucleus. This technique holds great promise for further studies of the incomplete fusion reaction.

a. <u>Fission Cross Section in the Fusion of the ^{64}Ni + ^{92}Zr Reaction</u>
(F. L. H. Wolfs, R. V. F. Janssens, T. L. Khoo, S. J. Sanders, R. Holzmann,* and W. C. Ma†)

As part of a study to understand the origin of neutron suppression observed in the decay of the compound nucleus ^{156}Er created with the ^{64}Ni + ^{92}Zr fusion reaction,[1] we have measured the fission cross section at several bombarding energies between 1.05 and 1.3 times the Coulomb Barrier. The fission cross sections were measured using the kinematic coincidence technique with two position-sensitive avalanche counters. The masses and energies of the fragments were obtained from the measured scattering angles and flight times. The measured fission yields combined with the previously measured evaporation residue yields provide the total fusion cross sections (Fig. I-4).

The competition between fission and light-particle evaporation is reproduced by statistical-model calculations with the code CASCADE and defines the diffuseness of the spin distribution of the compound nucleus to be $\Delta\ell = 4\hbar$. The calculated neutron multiplicities still overestimate the previously measured multiplicities. The difference can be reduced by replacing the normal yrast line used in the calculations with an elevated yrast line, suggesting that a fraction of the excitation energy is tied up in deformation during the neutron emission time.

The results of the fission measurements for ^{64}Ni + ^{92}Zr have been submitted for publication.

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[1]R. V. F. Janssens et al., Phys. Lett. <u>B181</u>, 16 (1986) and references therein.

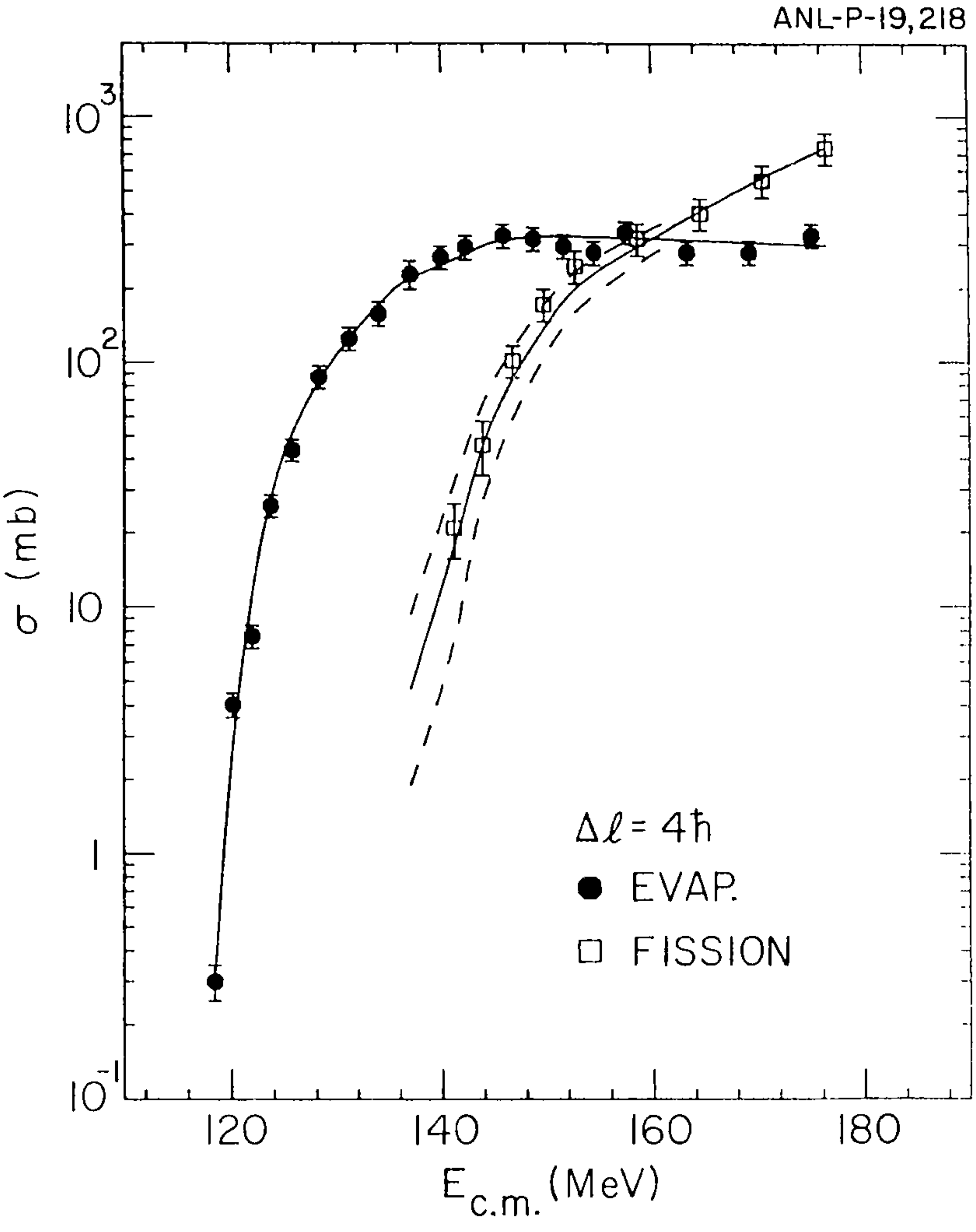

Fig. I-4. Comparison between the measured evaporation residue and fission yields (octagons and squares) and the results from statistical-model calculations (solid lines) using the code CASCADE for $\Delta \ell =$ $4\hbar$. The dashed lines indicate the error in the calculated fission yields induced by the uncertainties in the total fusion yield.

Edited by Karen J. Thayer

b. Sub-Barrier Fusion of ^{58}Ni + $^{144,154}Sm$ Measured using the BGO-CSG Array (R. R. Betts, R. V. F. Janssens, E. F. Moore, F. L. H. Wolfs, C. N. Pass,* J. S. Lilley,† and K. Beard‡)

Complementary to our studies of sub-barrier neutron transfer of ^{58}Ni + Sm we have measured the sub-barrier fusion of ^{58}Ni + $^{144,154}Sm$ using the ANL-Notre Dame BGO-CSG Array. The technique used was to identify fusion according to the sum energy and multiplicity of gamma rays measured in the BGO ball of the array. At the same time, ball-Ge coincidences allowed a measurement, and therefore normalization of the data, of discrete Coulomb excitation and transfer lines. The fusion of ^{58}Ni + ^{154}Sm, which is strongly deformed, is enhanced over the fusion with the spherical ^{144}Sm target as expected. This correlates well with the enhancement of the sub-barrier neutron transfer observed for the deformed Sm targets in recoil separator measurements.

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c. Experimental Study of the ^{60}Ni + ^{154}Sm Reaction (B. B. Back, S. J. Sanders, F. Videbaek, S. Kaufman, B. D. Wilkins, D. Henderson, B. G. Glagola, and J. G. Keller*)

The effects of the entrance-channel asymmetry in heavy-ion reactions are studied in this experiment. In an earlier experiment, using the reaction ^{32}S + ^{182}W, a more mass-asymmetric entrance channel leading to the same ^{214}Th compound system was studied. It was found that the fission-like fragments from this reaction behave essentially as expected for the decay of a compound system formed by the fusion of target and projectile. Only the angular anisotropy of the fragments were larger than expected for a compound reaction, indicating that a fraction of the fission-like strength originated from non-compound reactions, notably quasifission processes. The mass-angle correlations for this system were essentially commensurate with a compound-fission picture, showing only insignificant forward-backward asymmetries.

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In the ^{60}Ni + ^{154}Sm reaction, however, we find strong forward-backward asymmetries for the fission-like products indicating that these originate from a quasifission-type reaction with a reaction time which is shorter or comparable with the rotational period of the di-nuclear complex. From the angular distributions for specific mass splits, we have derived estimates of the reaction times as a function of the net mass transfer between the two participating nuclei. We find that the net transfer toward mass symmetry is consistent with an over-damped motion in a parabolic potential and that the associated characteristic time for mass equilibration is $\tau \sim 3.5 \times 10^{-21}$ s. This result compares well with the theoretical estimate of the $\tau \sim 3.9 \times 10^{-21}$ s obtained from the wall formula for one-body dissipation. Slightly longer ($\tau \sim 5.3 \times 10^{-21}$ s) characteristic times have been found earlier in ^{238}U-induced reactions, where correspondingly longer times were also expected theoretically. The present findings add empirical support for the notion that the dissipation mechanism for inducing nuclear distortions at low temperatures arises mainly from the interaction between the individual nucleons and the surface of the system which is the basis for the wall formula of Randrup and Swiatecki.

Present efforts are devoted to analyzing the deep-inelastic component of the total reaction cross section in order to derive reaction times for these processes and to compare them to theoretical predictions. Partial results from this experiment have been published, whereas a comprehensive manuscript is being prepared.

d. Distribution of Reaction Strength in the ^{48}Ti + ^{166}Er Reaction
(B. B. Back, S. J. Sanders, B. G. Glagola, D. Henderson, B. D. Wilkins, T. F. Wang, and J. G. Keller*)

The reaction ^{48}Ti + ^{166}Er has been studied as part of the program to determine the effects of entrance-channel mass asymmetry on the distribution of reaction strength between the dominant exit channels for the ^{214}Th composite system. Two other systems leading to ^{214}Th have been studied previously, and the results are available for comparison. Beams of ^{48}Ti with energies of 220, 240, 270, and 300 MeV were obtained from the ATLAS facility. Reaction products were detected in the angular range from 7.5° to 95° in an array of 9 singles Si-detectors and two Si-detector telescopes. The masses of the reaction products will be

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determined from the time of flight over the 40-to-75-cm distance from the target to the detectors by utilizing the excellent time structure of the beam. Complementary reaction products were detected in a position-sensitive avalanche detector of area 8 x 10 cm^2, which was located on the opposite side of the beam and centered at an angle of 50°. This arrangement allows for the verification of the two-body nature of the reactions being studied, by over-determining the kinematics for such processes. The data obtained in this experiment are presently being analyzed.

e. Energy Dissipation, Mass Flow and Excitation of the Tilting Mode in the $^{58}Ni + ^{208}Pb$ Reaction (B. B. Back, B. G. Glagola, S. J. Sanders, F. Videbaek, B. D. Wilkins, D. Henderson, J. G. Keller,* S.-M. Lee,† M. Ogihara,† and T. Nakagawa‡)

A study of the reaction mechanism in the $^{58}Ni + ^{208}Pb$ system has been undertaken using ^{58}Ni from the ATLAS facility at energies of E = 320, 410, 500, and 560 MeV. Reaction products, including elastic, quasi-elastic, deep-inelastic scattering products, as well as fission-like fragments were measured over the angular range from θ = 10° - 120° in an array of 12 single Si-detectors. The masses of reaction products were determined from the measured energy and flight time over the 40-60 cm distance from the target to the detectors. A position-sensitive avalanche detector was placed on the opposite side of the beam to register complementary reaction products from binary reactions and thereby verify the binary nature of the reaction. The data obtained in this experiment are presently being evaluated.

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f. Excitation of the Tilting Mode in Quasifission Reactions (B. B. Back, B. G. Glagola, K. E. Rehm, and S. J. Sanders)

The study of K-distributions, where K is the spin component along the fission axis in fission and quasifission reactions, has recently received much attention due to the observed deviations from expectations based on the standard fission theories. These studies are based on the measurement of the anisotropy of angular distributions, which are forward-backward symmetric in the center-of-mass frame of reference. In quasifission reactions between projectiles of ^{208}Pb, ^{238}U and targets of mass-30 and heavier, as well as in the $^{60}Ni + ^{154}Sm$

reaction, angular distributions showing distinct deviations from forward-backward symmetry have been observed. This shows that the composite system has made less than one revolution before re-separating into two quasifission fragments.

Although the standard theories for the angular distributions of fission fragments do not apply under these circumstances, it has recently been shown that a measure of the tilting of the inter-nuclear axis relative to the total spin may be obtained from measurements of the cross section near 0° and 180°. This tilting may be expressed in terms of the component, K, of the total spin, I, along the inter-nuclear axis. In the entrance channel, K is strictly zero for spinless projectiles and targets. If no tilting of the inter-nuclear axis, with respect to the total spin vector, occurred during the process, one would observe a singularity in the cross section at 0° (in the classical limit) simply because of the azimuthal angle degeneracy. The smearing of the initially-singular K-distribution, which occurs during the reaction via particle exchange and transfers between the reaction partners, will manifest itself by a much reduced pile up of cross section near $\theta = 0°$.

The main difficulty in studying the tilting mode in quasifission reactions arises from the abundance of elastically-scattered beam particles at small angles. In most cases it is impossible to measure the backward angles because the fragments emitted in this direction possess too low a kinetic energy to allow for reliable energy and time measurements of the fragments. In order to circumvent this problem we have measured fission-like products at angles of 5°, 7°, 10°, 15°, 20°,and 25° from the reaction $^{58}Ni + ^{208}Pb$ in the Area III Enge spilt-pole magnetic spectrograph. This is possible, even at the most forward angles, because the magnetic rigidity of the beam particles is slightly larger than those of the fission-like fragments. The energy and specific energy loss of the fission-like products were measured in the position-sensitive ΔE-E gas ionization detector positioned in the focal plane of the spectrograph. The experiment was carried out at beam energies of 410 and 500 MeV.

Because the charge resolution of the ΔE-E measurement is insufficient for the separation of individual elements, which would have enabled us to determine the Z of the fission-like fragments by simply counting the lines in the two-dimensional ΔE-E spectrum, we have performed a separate calibration experiment. In this experiment, a ^{109}Ag beam of 389 MeV was elastically scattered off targets of ^{58}Ni, ^{76}Ge, ^{92}Zr, ^{119}Sn, ^{154}Sm to produce energetic target recoils, which were measured at $\theta = 20°$ and 30° in the spectrometer. This provides us with calibration points for Z = 28, 32, 40, 50, and 62 at two different energies in the region of relevance.

The analysis of the data is presently in progress.

g. Stability Against Mass Asymmetry in Fission (B. G. Glagola, B. B. Back, H.-J. Körner, S. J. Sanders, B. D. Wilkins, and D. Henderson)

As part of the heavy-ion-induced fission program we have undertaken the study of the dependence of the fission-fragment mass distribution width on the fissility parameter. Previous measurements, involving light-ion reactions, concentrated on fissility parameters up to approximately x = 0.7 where the Liquid Drop Model predicts that the scission point begins to deviate from the saddle point. While the details of mass distributions for fission at low excitation energy are governed by the shell structure in the nascent fragments, the light-ion-induced fission data (30-65-MeV excitation energy) appear to reflect the stiffness against mass asymmetry at the saddle point. We believe that the excitation energy in the light-ion data was insufficient to eliminate the effects of shell structure at scission and have, therefore, undertaken measurements at higher excitation energy. An ^{16}O beam at 100 and 160 MeV was used to provide higher excitation energy (E^* = 45-75 and 105-130 MeV, respectively) while minimizing angular-momentum effects. Targets of ^{120}Sn, ^{154}Sm, ^{166}Er, ^{170}Yb, ^{175}Lu, ^{182}W, ^{197}Au, ^{208}Pb, and ^{238}U were used to span the fissility range $0.5 < x < 0.85$. The fission fragments were detected by kinematic coincidence in two Breskin-type counters placed on opposite sides of the beam. The kinematics for two-body reactions is overdetermined by measurement of the flight times and the x-y positions of the two fission fragments. The data have been presorted to separate out the coincident fragments. A Monte Carlo simulation of the data has been generated to allow the determination of the efficiency of the kinematic coincidence for the detector system. Analysis of the data is continuing with the generation of fission fragment mass and energy spectra.

h. Relaxation of Angular Momentum in U-induced Quasifission Reactions
(B. B. Back, S. Bjørnholm,* T. Døssing,* A. Gobbi,†
K. Hildenbrand,† and W. Q. Shen‡)

Binary reaction products from reactions of ^{238}U beam at energies of 4.6, 4.8, 5.9, 6.7, and 7.5 MeV/u with targets of ^{16}O, ^{26}Mg, ^{27}Al, ^{32}S, ^{nat}Cl, ^{40}Ca, ^{48}Ca, and ^{nat}Zn have been measured in kinematic coincidence. Beams were obtained from the UNILAC accelerator at G.S.I., Darmstadt. The multiplicities of associated γ-rays were measured in three NaI detectors, and presented as a function of fragment mass. A preliminary analysis indicates that all aligned and statistically excited spin modes of the fragments are fully populated in compound nucleus fission reactions. In quasifission reactions there are clear signs of a partial relaxation towards full statistical spin equilibrium. A manuscript presenting these results is presently being prepared.

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i. Spectroscopy of Fission Fragments from ^{56}Ni Decay (S. J. Sanders, B. B. Back, R. V. F. Janssens, D. G. Kovar, H.-J. Körner, T. L. Khoo, D. Henderson, G.-E. Rathke, T.-F. Wang, F. L. H. Wolfs, K. Beard,* and D. Habs,†)

We have measured the gamma radiations in coincidence with fission fragments from the decay of ^{56}Ni as populated through the ^{32}S + ^{24}Mg reaction. In previous measurements of the binary decay products from the ^{32}S + ^{24}Mg and ^{16}O + ^{40}Ca reactions, we showed that these products can be understood as resulting from the asymmetric fission of the ^{56}Ni compound nucleus. The relatively low temperature of the system at the saddle-point and the corresponding large role of shell effects lead to a strong mass dependence of the decay with the greatest cross sections found in the 4n, alpha-particle-like channels (eg. ^{12}C + ^{44}Ti). Since relatively little energy is available for the excitation of the fission fragments, it is plausible that the observed gamma-ray spectra for these fragments may reflect the structure of the nucleus at the scission point. A study of the gamma-ray spectra corresponding to specific

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final-mass channels can also lead to a better understanding of the isotopic dependence of the fission decay and the relative energy and angular-momentum sharing among the decay fragments.

In our measurement a large number (34 discrete channels) of Si (surface-barrier) detectors were mounted at angles between 8° and 45° in the new particle-scattering chamber for the Argonne-Notre Dame gamma-ray facility. These detectors subtended a total solid angle of about 70 msr. A pulsed, 140-MeV ^{32}S beam from the ATLAS facility was incident on a self-supporting ^{24}Mg target. Particle mass identification was achieved by time-of-flight measurement using the rf beam structure of the ATLAS machine. The coincident gamma-ray spectra were obtained using eight Compton-suppressed Ge detectors. In addition, a 42-element BGO array was arranged about the target to obtain multiplicity and sum-energy information. An interesting observation is that only members of $K\pi = 3^-$ and $K\pi = 5^-$ bands are found to show any significant strength aside from the transitions between the lowest ground-state band members. The 3^- band is thought to have a strong octupole nature and it is possible that the observed strength to this band results from the octupole deformation of the fragments at the scission point. The importance of nuclear deformation at the scission point may also be indicated by the observation that the secondary evaporation products as identified by the emitted gamma rays deviate from the expectations of statistical evaporation codes. For example, when a ^{12}C particle is identified in one of the particle detectors the unobserved ^{44}Ti recoil may (and usually will) have sufficient excitation energy to particle decay. The probability of its decay to specific final channels (via p,n, or alpha emission) can be determined by identifying the characteristic radiations from these channels. We find large differences between the observed recoil evaporation and what would be expected from the statistical-model calculations of this decay. The analysis of these experimental results is still in a relatively early stage.

j. Study of the Binary (Fission) Decay of ^{56}Co (S. J. Sanders, B. B. Back, R. V. F. Janssens, D. G. Kovar, T.-F. Wang, and F. W. Prosser*)

We have studied the fission decay of ^{56}Co as populated with the ^{29}Si + ^{27}Al reaction to determine the role of shell effects in this decay process. A coincidence technique, previously developed to study the decay of ^{56}Ni, was employed allowing for the reconstruction of the primary mass dependence of the decay prior to secondary light-particle emission. In our previous measurement of the ^{32}S + ^{24}Mg system (reaching the ^{56}Ni compound system) we discovered the preferential decay to mass asymmetric fission channels with the greatest cross sections in channels where both reaction fragments have a 4N, alpha-particle-like structure. The present measurement precludes the binary decay to such strongly bound exit channels. A comparison of the fission of ^{56}Co and ^{56}Ni should lead to a better understanding of this process in light systems and, in particular, should illuminate the role of shell effects.

The experimental arrangement consisted of seven Si (surface barrier) detectors on one side of the beam axis and two, large-area multi-wire proportional counters on the opposite side of the beam. Beams of 125-MeV and 160-MeV ^{29}Si were incident on self-supporting ^{27}Al foils. From the Si detectors, which were located between 7° and 49°, the mass of one of the reaction products could be determined using the time-of-flight technique. The velocity and angle of the recoiling fragment could then be determined by the proportional counters. These counters completely covered the angular range between 8° and 55° in two settings. With the coincidence information it is possible to deduce the primary, pre-evaporation masses of the decay products. Our on-line analysis indicated the clear presence of fission decay at each of the energies measured, although off-line analysis will be necessary to fully characterize the mass dependence of this process for comparison with the ^{56}Ni results.

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k. Breakup of ^{40}Ca Following Inelastic Scattering (R. R. Betts, B. B. Back, B. K. Dichter, S. J. Sanders, B. R. Fulton,* S. J. Bennett,* S. Allcock,† and A. E. Smith†)

Recent experiments have shown that the breakup of light nuclei such as ^{24}Mg and ^{28}Si into symmetric and near-symmetric channels proceeds through a set of specific states in the vicinity of the effective threshold for the decay. These states do not appear to overlap the known resonances in the decay channels or coincide with known fragments of the giant resonance strength.

An interpretation of these observations in terms of a simple model due to Harvey, leads to the conclusion that the details of the breakup depend on the deformation of the parent nucleus and on the manner in which it is excited. One interesting prediction of this model is that ^{40}Ca should preferentially decay to ^{28}Si + ^{12}C in their ground states after the ^{40}Ca has been excited via inelastic scattering.

We have recently performed an experiment at ATLAS to test this prediction. A 300-MeV beam of ^{40}Ca was used to bombard a ^{12}C target mounted in the 36" scattering chamber. A close-packed array of X-Y position-sensitive ΔE-E telescopes was used to detect coincident pairs of particles. The measurement of energies and angles of the identified pairs is sufficient to fully determine the kinematics of the three-body final state and, for decays to the ground states of the detected particles, determine the excitation energy of the initially excited nucleus. Analysis, in Birmingham, of the results of this experiment is still in progress but on-line results indicate that decays to ^{12}C + ^{28}Si are in fact observed and that the expectations of the Harvey model are borne out.

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ℓ. Fission-like Decay of ^{80}Zr Formed via ^{40}Ca + ^{40}Ca (R. R. Betts, B. B. Back, D. J. Henderson, S. J. Sanders, F. Videbaek, B. D. Wilkins, B. K. Dichter,* P. M. Evans,† and A. E. Smith†)

Fully-damped fragments from the ^{40}Ca + ^{40}Ca system have been measured at bombarding energies of 197 and 230 MeV. The experiment used six time-of-flight telescopes in the angular range 10 to 50 degrees operated in singles and coincidence with a large-area multi-wire counter backed by a Bragg-curve ionization chamber.

The distribution of the damped events in both energy and angle follow the familiar pattern characteristic of the decay of a long-lived system and the overall mass distribution is seen to be Gaussian, peaked close to symmetry. This last observation is in contrast to that for similar data for ^{28}Si + ^{50}Cr which populates the adjacent compound nucleus ^{78}Sr in the same region of excitation energy and angular momentum. The ^{28}Si + ^{50}Cr damped fragments have a mass distribution peaked close to the target and projectile, inconsistent with the notion that both reactions proceed through normal compound-nucleus fission.

On the basis of the rotating-liquid-drop model, it would have been expected that both these compound nuclei should fission symmetrically. Calculations with the finite-range liquid-drop model, however, indicate that the observed cross sections likely originate from partial waves for which the compound-nucleus fission barrier has already vanished. The observed damped yields are therefore more consistently described in terms of the fast fission process familiar from much heavier systems. This is the first time that this process has been identified in this mass region and thus provides a link between orbiting phenomena observed in lighter systems and damped processes in heavier systems. This work has formed the basis of the D.Phil. thesis of P. M. Evans and has been submitted for publication.

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m. Evaporation Residue Cross Section Behavior for $^{16}O + ^{40}Ca$ at $E_{lab} = 13.4$ MeV/u (D. G. Kovar, C. Beck, D. J. Henderson, R. V. F. Janssens, S. J. Sanders, T.-F. Wang, T. Moog, W. C. Ma,* M. Vineyard† C. F. Maguire,‡ F. W. Prosser,§ and G. Rosner¶)

The analysis of the singles measurements of evaporation residues produced in the $^{16}O + ^{40}Ca$ reaction at $E_{lab}(^{16}O) = 13.4$ MeV/nucleon was completed and submitted for publication. The total cross sections for evaporation residues from complete and incomplete fusion were extracted utilizing velocity spectra predicted by evaporation codes. Model simulations of two sources and multi-sources indicate that the details of the velocity distributions of the evaporation residues as a function of mass and detected angle are sensitive to the character of the pre-equilibrium light particles emitted. The results indicate that substantial single- or two-nucleon pre-equilibrium emission processes are present and that heavy particle (A > 4) evaporation occurs. The extracted maximum evaporation-residue cross section, consistent with complete fusion, was found to be 475 mb; a value significantly smaller than had been previously reported and in basic agreement with the cross sections observed in other entrance channels forming the ^{56}Ni compound nucleus. A lower limit on the cross section for incomplete fusion of 230 mb was established. Cross sections of the order of 100 mb were established for yields consistent with fission, but the measurements were unable to establish whether these yields originated from complete or incomplete fusion. The analysis of results obtained in the coincidence measurements performed for the same reaction is underway.

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n. <u>Energy Dependence of Complete and Incomplete Fusion in $^{28}Si + {}^{28}Si$</u>
(D. G. Kovar, D. J. Henderson, R. V. F. Janssens, B. D. Wilkins, C. Beck,* M. Vineyard,† C. F. Maguire,‡ F. W. Prosser,§ and G. S. F. Stephans¶)

The analysis of results obtained in time-of-flight measurements for the $^{28}Si + {}^{28}Si$ reaction at bombarding energies of 11, 14.3, and 16 MeV/u were completed. The measurements had been motivated by (1) the observation of a significantly different behavior of the evaporation-residue cross section for the $^{16}O + {}^{40}Ca$ and $^{28}Si + {}^{28}Si$ reactions (forming ^{56}Ni) at laboratory bombarding energies greater than 8 MeV/u, and (2) evidence for significant incomplete fusion cross section in the case of $^{16}O + {}^{40}Ca$, which appears to be absent in the $^{28}Si + {}^{28}Si$ case. The absence of incomplete fusion yields for the symmetric entrance channel $^{28}Si + {}^{28}Si$, if true, would suggest an entrance-channel dependence for the incomplete fusion process. The observed evaporation-residue velocity distributions were found to be broader than predicted by evaporation calculations. The component of the evaporation-residue yields, consistent with complete fusion, was extracted using the predicted velocity distributions to obtain upper limits for the complete fusion evaporation-residue cross sections. The extracted maximum cross sections for complete fusion at 11, 14.3, and 16 MeV/nucleon are found to constitute 70%, 62%, and 61%, respectively, of the total evaporation-residue cross section. These extracted complete fusion cross sections are in basic agreement with those obtained in our recent analysis of the results for the $^{16}O + {}^{40}Ca$ reaction (section I.B.m.), resolving the apparent entrance-channel dependence in the evaporation-residue cross sections that had existed in the literature. On the other hand, the present results provide additional evidence of an entrance-channel dependence for the probability for incomplete fusion processes (i.e., for reactions occurring at the same relative velocity there is significantly smaller probability for incomplete fusion processes for mass symmetric entrance channels than for mass asymmetric entrance channels.)

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o. Identification of Incomplete Fusion in the ^{12}C + ^{160}Gd Reaction at E_{lab} = 10 MeV/u: Evaporation Residue - Gamma-Ray Coincidence Measurements (D. G. Kovar, B. B. Back, B. G. Glagola, D. J. Henderson, R. V. F. Janssens, E. F. Moore, S. J. Sanders, K. Beard,* C. F. Maguire,† and M. Vineyard‡)

Coincidence measurements between evaporation residues and gamma rays were performed for the ^{12}C + ^{160}Gd reaction at $E_{lab}(^{12}C)$ = 120 MeV. In previous singles measurements of ^{12}C-induced reactions on targets of ^{90}Zr, ^{120}Sn, ^{160}Gd, and ^{197}Au over an energy $4 < E_{lab} < 11$ MeV/u the velocity spectra of the evaporation residues showed evidence of a distinguishable incomplete fusion component which was identified with pre-equilibrium alpha emission. The incomplete fusion component was present at low bombarding energies near the Coulomb barrier and then grew rapidly with bombarding energy accounting for ≃ 25% of the evaporation residue yields at E_{lab} = 10 MeV/nucleon. The present measurement was performed to extract the velocity spectra associated with the various evaporation-residue isotopes produced and verify the identification of the incomplete fusion component in the velocity spectra. The evaporation residues, detected in a low-pressure, position-sensitive PPAC (spanning the angular range 7-22 degrees at 32 cm from the target), were measured in coincidence with the gamma rays detected in six Compton-suppressed germanium detectors and 35 BGO detectors. The velocity spectra (obtained from timing measurements with respect to the beam RF) associated with evaporation-residue isotopes (identified by their gamma-ray transitions) were extracted. For some isotopes the velocity distributions were centered at the velocity expected for complete fusion, while for others they were shifted to lower velocities. The shifted velocity spectra are associated with Er isotopes, which are not predicted to be produced strongly in a ^{12}C + ^{160}Gd reaction, but are expected to be produced strongly in a ^{8}Be + ^{160}Gd reaction. The magnitude of the velocity shift is consistent with the pre-equilibrium emission of a beam-velocity alpha particle. The angular distributions and gamma-ray multiplicities associated with the evaporation-residue isotopes from complete fusion and incomplete fusion were extracted and found to differ significantly. This technique for the extraction of the velocity spectra of evaporation-residue isotopes is very promising as a tool for the quantitative identification of incomplete fusion yields to be pursued in studies next year.

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p. Fusion-Evaporation Cross Sections for $^{24}Mg + ^{24}Mg$ at $5 < E_{lab} < 9$ MeV/u
(D. G. Kovar, F. W. Prosser,* S. V. Reinert,* G. Rosner,† G. S. F. Stephans,‡ J. J. Kolata,§ A. Szanto de Toledo,¶ and E. Szanto¶)

Complete angular distributions of the heavy evaporation residues from the fusion of $^{24}Mg + ^{24}Mg$ were obtained at beam energies of 111, 160, and 206 MeV and used to obtain the total fusion-evaporation cross sections. It was found that the cross sections at the higher energies decrease in a manner indicative of a limiting angular momentum for fusion, as seen in other symmetric target projectile systems such as $^{28}Si + ^{28}Si$. The analysis of these data was completed some time ago, but extensive comparisons of the results to the prediction of evaporation codes, particularly PACE, have only recently been completed. Very good agreement has been obtained between experiment and theory at the two lower energies, but significant discrepancies appear at 206 MeV. These are interpreted as evidence for the onset of incomplete fusion, but it is impossible to distinguish whether these discrepancies stem from this process or from an increased evaporation of heavier nuclei, e.g., ^{8}Be. The areas of agreement at the lower energies include the centroids and widths of the distributions of residue masses, the angular distributions of the residues, the detailed shapes of the invariant velocity distributions for the individual residue masses, the deviation of the centroids of these distributions from $v_{CN}\cos\theta$ with increasing angle, and the step-wise increase in the widths of these distributions with the onset of increasing numbers of alpha particles in the evaporation chain. It has been shown that forcing the emission of light particles to be isotropic in the center-of-mass system in the PACE calculations results in significantly poorer agreement with the shapes and centroids of the experimental velocity distributions. This is evidence that the actual angular distributions are also anisotropic. At 206 MeV, the experimental angular

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distributions are significantly broader than those predicted by PACE and only marginal improvement is obtained by assuming the presence of incomplete fusion. Also, the velocity distributions become systematically broader than predicted with decreasing residue mass. Whether these effects can be explained in detail by assuming that nuclei heavier than alpha particles participate in the evaporation process awaits the enhancement of PACE to include this possibility. It is clear that only coincidence measurements can resolve these questions experimentally.

q. Energy Dependence of Fusion Evaporation Residue Cross Sections in the $^{28}Si + ^{28}Si$ Reaction (M. F. Vineyard,* J. S. Bauer* C. H. Gosdin,* R. S. Trotter,* D. G. Kovar, C. Beck, D. J. Henderson, R. V. F. Janssens, B. D. Wilkins, J. F. Mateja,† C. F. Maguire,‡, F. W. Prosser,§ and G. S. F. Stephans¶

The analysis of time-of-flight measurements of the evaporation residue velocity distributions for the $^{28}Si + ^{28}Si$ reaction at bombarding energies of 309, 397, and 452 MeV has been completed. The measurements were motivated by the earlier observations[1] of a large difference in the evaporation residue cross sections for the $^{16}O + ^{40}Ca$ and $^{28}Si + ^{28}Si$ systems (forming ^{56}Ni) at bombarding energies above 8 MeV/u. Also, there was evidence of a significant incomplete fusion cross sections for the $^{16}O + ^{40}Ca$ system, which appears to be absent in the $^{28}Si + ^{28}Si$ system. The absence of incomplete fusion yields for the symmetric entrance channel $^{28}Si + ^{28}Si$, if true, suggests an entrance channel dependence for the incomplete fusion process. The evaporation residue velocity distributions observed in the present study were found to be broader than predicted by evaporation calcúlations. The component of the evaporation residue yields consistent with complete fusion was extracted using the predicted velocity distrubitons to obtain upper limits for the complete fusion evaporation residue cross sections. These cross sections are compared with the results

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[1]D. G. Kovar, Proc. 5th Adriatic Int. Conf. on Nuclear Physics, Croatia, Yugoslavia, Sept. 1984 (World Scientific 1984) pp. 185-204.
[2]G. Rosner et al., Bull. Am. Phys. Soc. 28, 670 (1983)
[3]S. B. DiCenzo et al., Phys. Rev. C23, 2561 (1981).
[4]Y. Nagashima et al., Phys. Rev. C33, 176 (1986).
[5]C. Beck et al., submitted to Phys. Rev. C.

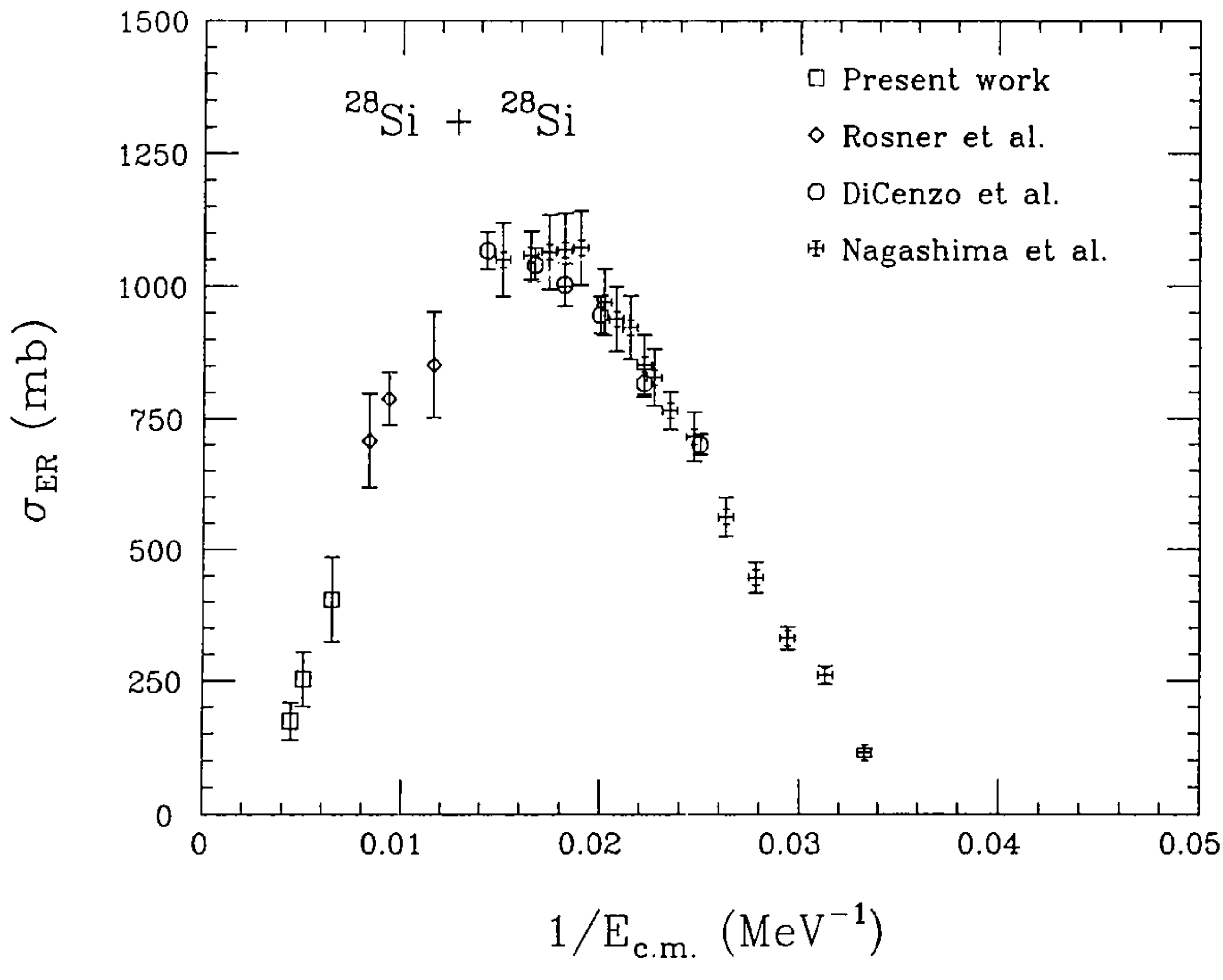

Fig. I-5. Total evaporation residue cross sections for complete fusion extracted in the present study are compared to those reported for lower bombarding energies (Refs. 2-4).

of previous lower-energy measurements[2-4] in Fig. I-5. The extracted maximum cross sections for complete fusion at 309, 397, and 452 MeV are found to constitute 70%, 62%, and 61%, respectively, of the total evaporation residue cross section. These extracted complete fusion cross sections are in basic agreement with those obtained in our recent analysis of the results for the ^{16}O + ^{40}Ca reaction,[5] moving the apparent entrance-channel dependence in the evaporation residue cross sections. On the other hand, the present results provide additional evidence of an entrance-channel dependence of the probability for incomplete fusion processes (i.e., for reactions occurring at the same relative velocity there is significantly smaller probability for incomplete fusion processes for mass symmetric entrance channels than for mass asymmetric entrance channels.)

C. HIGH ANGULAR-MOMENTUM STATES IN NUCLEI

The research program focusses on three major areas: (a) studies of nuclear structure at very high spins on and above the yrast line, (b) investigations of the properties of the compound nucleus decay and (c) research on reflection asymmetric nuclear shapes.

Research on nuclear structure at very high spin concentrated mainly on superdeformation. After the discovery at Daresbury of a band of 19 transitions corresponding to the rotation of the superdeformed ^{152}Dy nucleus (axis ratio of roughly 2:1), some of the important questions to be answered concern the existence of (i) other superdeformed nuclei in the same region and (ii) the existence of other regions of the nuclear chart where superdeformation occurs. Evidence for a band of 19 (possibly 20) transitions with an energy spacing consistent with superdeformation was found in ^{151}Dy. The band has similarities with the one seen in ^{152}Dy. The differences in the behavior of the static and dynamic moments of inertia in the two cases yield information on the role of high-j orbitals from the next shell. In another experiment, preliminary evidence for superdeformation in the A = 190 region was found. A band of 12 transitions was found in ^{191}Hg. The energy spacings are consistent with the very large moments of inertia expected for a superdeformed shape. Experiments aimed at establishing the quadrupole moment in the band will take place soon in order to determine the deformation more accurately. Finally, an experiment aimed at the understanding of the feeding mechanism of the superdeformed bands was also performed. In this experiment it was shown that in the case of ^{152}Dy the entry point in the nucleus for states in the superdeformed band is located at much higher spin and at an excitation energy closer to the yrast line than for the other (single-particle like) yrast states. Differences between the quasicontinuum radiation associated with the two structures has also been studied.

Information on the properties of the compound-nucleus decay came from two types of investigations. The gamma decay of the compound nucleus after particle evaporation was studied by measuring the total γ-ray spectrum with Compton-suppressed Ge detectors (CSG's). Over the last years, this study has focussed on a comparative analysis of the quasicontinuous part of the spectra from ^{152,154,156}Dy when these three nuclei are produced with very similar angular momenta and excitation energies. In particular, the pronounced collective E2 component of the γ-quasicontinuum in the transitional nucleus ^{154}Dy is split into two distinct parts, signifying a structural change along the γ cascade above the yrast line. This splitting does not occur in ^{152,156}Dy. The E2 and statistical components are reproduced in simple γ cascade calculations; in ^{152}Dy and ^{156}Dy only rotational bands are included, whereas in ^{154}Dy additional vibration-like transitions are required to reproduce the two peaks.

Our investigations of the stage preceding γ-ray emission focussed on the origin of the suppression of neutron emission seen in some heavy-ion induced fusion reactions. During the past year, a comparison of the partial-wave cross sections for fusion of ^{64}Ni + ^{92}Zr and ^{64}Ni + ^{96}Zr was performed at energies of ~ 5% above the Bass-model fusion barrier. The partial wave distribution for fusion was found to be very different in the two cases. Also the energy and angular distribution of charged particles emitted in fusion reactions were studied with particle-γ coincidences. A comparison between the proton and alpha spectra measured for the decay of the same compound nucleus ^{156}Er differ appreciably when the nucleus is formed with the $^{12}C + ^{144}Sm$ and $^{64}Ni + ^{92}Zr$ reactions at the same compound- nucleus excitation energy. It appears that the initial stage of the decay could be influenced by shell-structure effects.

Research on octupole shapes continued to focus on the new region of octupole deformation discovered at this laboratory two years ago, i.e. the region of very neutron-rich nuclei around ^{146}Ba. These nuclei cannot be studied with the usual in-beam techniques because of their large neutron excess and the level schemes have been derived from an experiment where γ-γ coincidences from ^{252}Cf fission fragments were measured. As in the case of $^{144,146}Ba$, interlaced positive- and negative-parity levels connected by fast electric-dipole transitions have been observed in ^{146}Ce but not in $^{148,150}Ce$. This can be accounted for in theoretical calculations. Studies of reflection asymmetric shapes in actinide nuclei have also continued. Firm evidence for octupole deformation in ^{223}Ac has come from an experiment with the LISOL isotope separator at Louvain-la-Neuve. Studies of new band structures in the light Th isotopes have just started. In the latter, the experiment involved a coincidence measurement between the γ-rays and the evaporation residues in order to discriminate against γ-rays from fission.

All projects described in this section have taken advantage of the capabilities of the Argonne-Notre Dame BGO γ-ray facility which was completed at the end of last year. Thus, the full system of 50 hexagonal BGO detectors (used mainly as a sum-energy/multiplicity filter) surrounded by 12 CSG's is available for the experiments. Furthermore, a scattering chamber for coincidence measurements between γ-rays and particles identified either by ΔE-E or time-of-flight techniques is now available. A support structure for up to 7 CSG's also exists at the spectrograph for particle-γ coincidence experiments with this instrument. Design studies are taking place to use the entire facility in conjunction with the Fragment Mass Analyzer.

Several projects are joint efforts with outside user groups from Notre Dame, Purdue, INEL-Idaho, GSI, Heidelberg, Giessen, Montreal and Tennessee Technical University.

a. Superdeformation in ^{151}Dy (G.-E. Rathke, R. V. F. Janssens, I. Ahmad, M. Hass, T. L. Khoo, H.-J. Körner, F. L. H. Wolfs, W. C. Ma,* M. W. Drigert,† K. Beard,‡ U. Garg,‡ S. Pilotte,§ and P. Taras§)

As part of our efforts to identify the nuclei at the beginning of the rare-earth region where superdeformation occurs, we have studied the nucleus ^{151}Dy. This experiment was performed with the Argonne-Notre Dame BGO γ-ray facility. The reaction ^{122}Sn(^{34}S,5n) was used at a beam energy of 174 MeV. The target consisted of 3 thin self-supporting 300-μg/cm^2 foils. The recoiling nuclei were stopped 10 cm from the target in a Pb foil. Events where at least 2 Ge detectors and 5 elements of the inner array fired were recorded on tape together with the multiplicity and sum-energy information. Identification of the final nuclei by isomer tagging was also possible and the relevant time and multiplicity information was also collected. A total of 330 x 10^6 coincidence events was accumulated.

A rotational band of 19 (possibly 20) transitions extending to a spin of about 131/2 $\hbar$ has been observed with an average dynamic moment of 79 $\hbar$ MeV^{-1}. This value is close to that measured for other nuclei in this mass region[1-3] and is close also to that expected for a superdeformed band in cranked Strutinsky calculations by Chasman (see IV.A.f.). Similarities as well as striking differences with the superdeformed bands of neighboring nuclei are observed (Fig. I-6). In particular, the evolution of the static and dynamic moments of inertia as a function of rotational frequency can be examined. In the ^{151,152}Dy isotopes the values of the two moments become essentially constant at the highest spins and have values very close to each other, the difference being somewhat larger in ^{151}Dy. We note that for ^{151}Dy the value of the static moment of inertia exceeds that of the dynamic moment of inertia at all frequencies while, in contrast, the opposite occurs in ^{152}Dy. Furthermore, while the static moment of inertia decreases and the dynamic moment increases in value with rotational frequency in

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[1]P. J. Twin et al., Phys. Rev. Lett. 57, 811 (1986).
[2]B. Haas et al., Phys. Rev. Lett. 60, 503, (1988).
[3]M. A. Deleplanque et al., Phys. Rev. Lett. 60, 1626 (1988).

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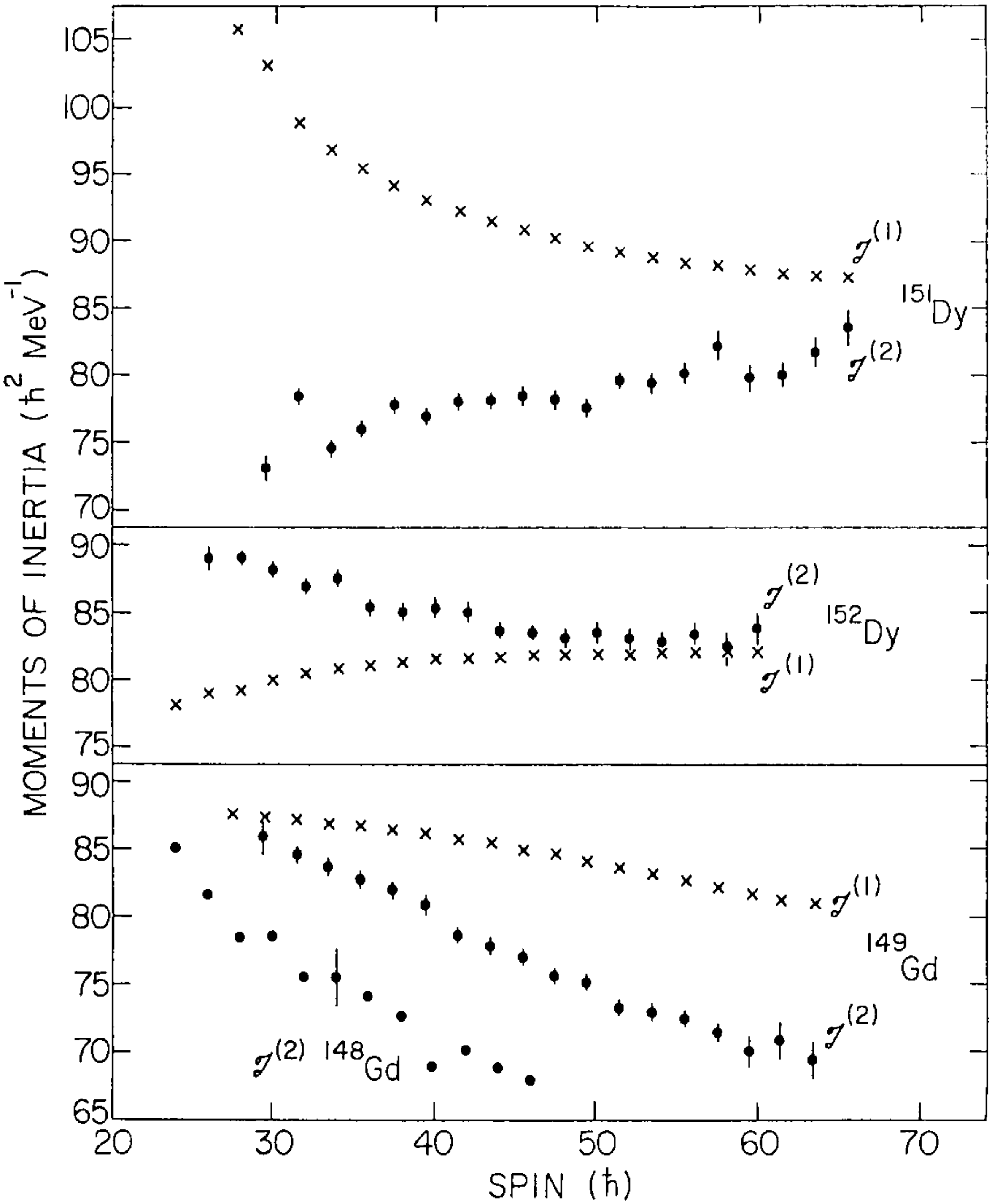

Fig. I-6. Static ($\mathcal{J}^{(1)} = (1I-1)\hbar^2/\Delta E_\gamma$) and dynamic ($\mathcal{J}^{(2)} = 4\hbar^2/\Delta E_g$) moments of inertia for the nuclei ^{151}Dy (top), ^{152}Dy (middle) and ^{149}Gd (bottom) as a function of spin. The $\mathcal{J}^{(2)}$ moment of inertia for ^{148}Gd has been added for comparison, assuming that the spin of the lowest member of the band is I=24 $\hbar$.

^{151}Dy, the opposite happens in ^{152}Dy. These differences may reflect the influence of particles excited into high N-shells. Thus, there is hope that these results will contribute to the understanding of the underlying microscopic structure.

In this experiment (as in all other cases where superdeformation was observed in this region) the transitions linking the superdeformed band to the known yrast line could not be observed and it is likely that many different decay paths share the intensity. Thus, the excitation energy of the superdeformed band and the spin of the various levels were not determined accurately. In order to gain more insight into this question a second experiment with a thick target was performed with the hope that the yrast states of ^{151}Dy will be established in the spin and energy range where they are close to the superdeformed states. This experiment is currently under analysis. Further effort in the analysis concentrates on the quasi-continuum radiation. Experiments aimed at identifying superdeformed bands in other nuclei are planned.

b. Search for Superdeformation in the Heavy Mercury Isotopes
(R. V. F. Janssens, E. F. Moore, I. Ahmad, T. L. Khoo, F. L. H. Wolfs, D. Ye,* K. Beard,* U. Garg,* Z. W. Grabowski,† and M. W. Drigert‡)

Superdeformation was first proposed some twenty years ago to explain the fission isomers observed in the actinides. The interest in the mechanisms responsible for exotic shapes (i.e. mainly shell effects) has increased enormously with the discovery of a discrete line superdeformed band in ^{152}Dy.[1] Currently several nuclei around ^{152}Dy have been shown to exhibit superdeformed rotational structures, among them the ^{151}Dy nucleus studied at this laboratory.[2] One of the intriguing questions concerning superdeformation is whether there are other experimentally accessible regions of the periodic table in which superdeformation can be found.

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[1]P. J. Twin et al., Phys. Rev. Lett. 57, 811 (1986).
[2]G.-E. Rathke et al., Phys. Lett. B209, 177 (1988).

Calculations by R. R. Chasman, described elsewhere in this report, have suggested that the A = 190 region is particularly interesting in that there are large Coulomb effects here that favor large deformations, in addition to rotational energy effects associated with high angular momenta. In the ^{191,192}Hg nuclei for example, a superdeformed minimum is calculated to be yrast at spins in excess of 30 $\hbar$ with a well depth of about 3 MeV. This minimum can be associated with a large gap in the proton particle spectrum at Z = 80, and a somewhat smaller gap in the corresponding neutron spectrum at N = 112. The calculated axis ratio is 1.65. We have studied the ^{191,190}Hg isotopes with ^{36}S-induced fusion reactions on a ^{160}Gd target. While the background in the γ-ray spectra due to fission is certainly somewhat higher than the one observed in comparable measurements in the rare-earth region, meaningful experiments are still possible because of the excellent background reduction achieved with the Argonne-Notre Dame BGO facility.

The data were taken in early December and the analysis is still underway. Preliminary results indicate the presence of two bands of transitions 37 keV apart on average. This energy spacing corresponds to a dynamic moment of inertia of 110 $\hbar$ MeV^{-1} expected for very large deformations. One of the bands is assigned to de-excitations in the ^{191}Hg nucleus and is shown in Fig. I-7. The second band is of much weaker intensity and more difficult to analyze. Preliminary indications are, however, that it corresponds to de-excitations in ^{190}Hg. In contrast with the superdeformed bands observed in the A = 150 region, these bands feed the known yrast states very close to the ground state indicating that the superdeformed minimum persists down to the lowest spins. More experiments, including lifetime measurements, are planned in order to measure the deformation of the states in the band directly. The analysis of the present data is continuing.

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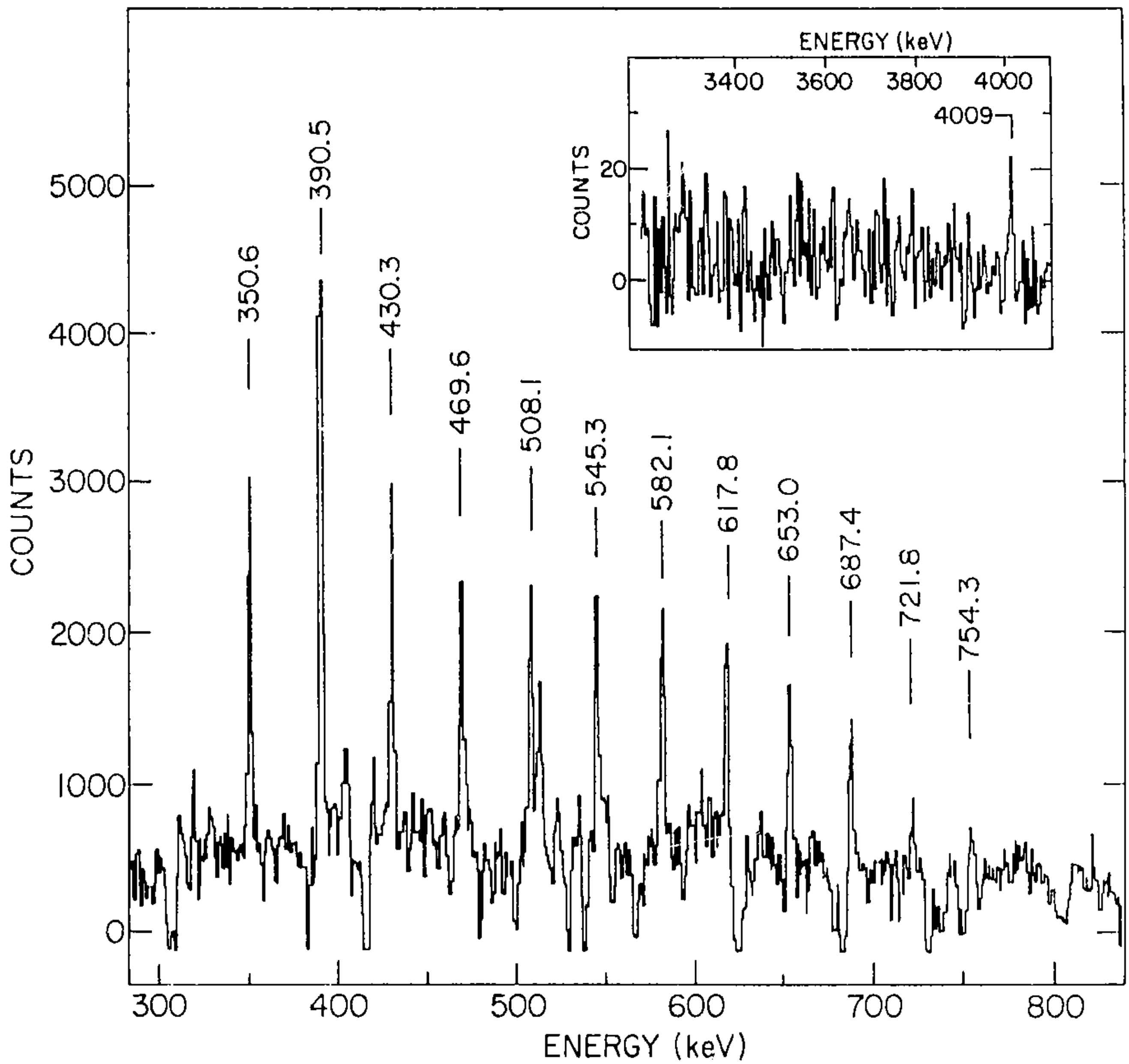

Fig. I-7. γ-ray spectrum in ^{191}Hg obtained by summing coincidence gates on selected transitions (351, 471, 508, 545, 582 and 653 keV). The γ-ray at 514 keV is an identified contaminant. A 4009-keV line which could represent a link between the superdeformed states and the $17/1^+$ yrast state is shown in the inset.

c. Feeding of Superdeformed Bands (E. F. Moore, T. L. Khoo, R. V. F. Janssens, I. Ahmad, M. Hass, H.-J. Körner, G.-E. Rathke, F. L. H. Wolfs, W. Ma,* K. Beard,† U. Garg,† D.-Z. Ye† M. Drigert‡ and Z. Grabowski§))

Discrete-line superdeformed bands have been observed with unexpectedly large intensities (up to 2% of the ground-state transition strength). We have performed experiments in an attempt to ascertain the mechanism for the larger-than-expected population strength. The main aims were to measure the average spin I_i and sum energy E_i of the so-called entry points (following neutron evaporation) and the spectrum of the quasicontinuum γ rays preceding both the prolate superdeformed band and yrast oblate states in ^{152}Dy.

In the reaction $^{120}Sn(^{36}S,4n)^{152}Dy$, with 172-MeV ^{36}S beams it was found that (I_i,E_i) for the oblate and superdeformed states were (52 $\hbar$, 34 MeV) and (70 $\hbar$, 35 MeV), respectively. Hence, the initial spin associated with the superdeformed states is significantly larger, whereas the sum energy is only marginally different. These results suggest that the initial superdeformed band population is quite cold, with an excitation energy around 1-2 MeV with respect to the expected position of the superdeformed band. This "cold" population could account -- at least in part -- for the observed trapping inside the superdeformed secondary minimum, resulting in the striking sequence of 19 equi-spaced γ transitions.

Our data suggest that the statistical γ yield associated with superdeformed band is significantly lower than that associated with the oblate states, although the statistics are rather marginal. (This is consistent with "cold" population.) We intend to examine the statistical spectra measured in the BGO "ball" elements in order to make a more definitive statement on this point. We also hope to understand how neutron decay to the superdeformed states, despite the large initial spin, successfully compete against fission.

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d. Structural Changes Along and Above the Yrast Line of ^{154}Dy (T. L. Khoo, I. Ahmad, B. Dichter, H. Emling, R. Holzmann, R. V. F. Janssens, T. F. Wang, W. C. Ma,* M. Quader,† P. J. Daly,† Z. Grabowski,† M. Piiparinen,† W. Trzaska,† M. W. Drigert,‡ and U. Garg§)

Rapid rotation may induce dramatic structural changes in some nuclei. The properties of these nuclei provide a stringent test for nuclear models. The transitional nucleus ^{154}Dy was the first nucleus in which a transition from a prolate shape to an oblate shape was found.[1] Theory accounts for this switch in terms of band termination, a process where the shape associated with a given initial configuration having a prolate deformation changes gradually with angular momentum until it reaches the oblate limit.

This picture has so far been checked mainly by comparing experimental and calculated energies of yrast levels in transitional nuclei. It is important to extend these comparisons to non-yrast levels as well. Furthermore, other quantities such as lifetimes should also be measured. The latter provide a direct measure of collectivity. Finally, by tracing the yrast line to higher spins one can ascertain if the oblate coupling scheme persists beyond the maximum spin which can be generated by the valence nucleons.

With these motivations in mind, we performed a series of experiments at ATLAS using the BGO gamma-ray facility to study the high spin structure of ^{154}Dy.

More than 50 new transitions have been placed in the level scheme of ^{154}Dy (Fig. I-8). An impressive series of nuclear-structure changes along the yrast line have been observed: the ground-state band (gsb) is crossed at 16^+ by an aligned $\nu i_{13/2}$ S-band, which then continues as the yrast structure to 32(+), while the gsb continues as an excited band to 26^+. Both bands are crossed at these spins by structures whose irregular energies and lifetimes suggest the approach toward aligned-particle configurations. However, for spin 38^+ - 48^+,

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[1]A. Pakkanen et al., Phys. Rev. Lett. 48, 1530 (1982) and H. W. Cranmer -Gordon, Nucl. Phys. A465, 506 (1987).

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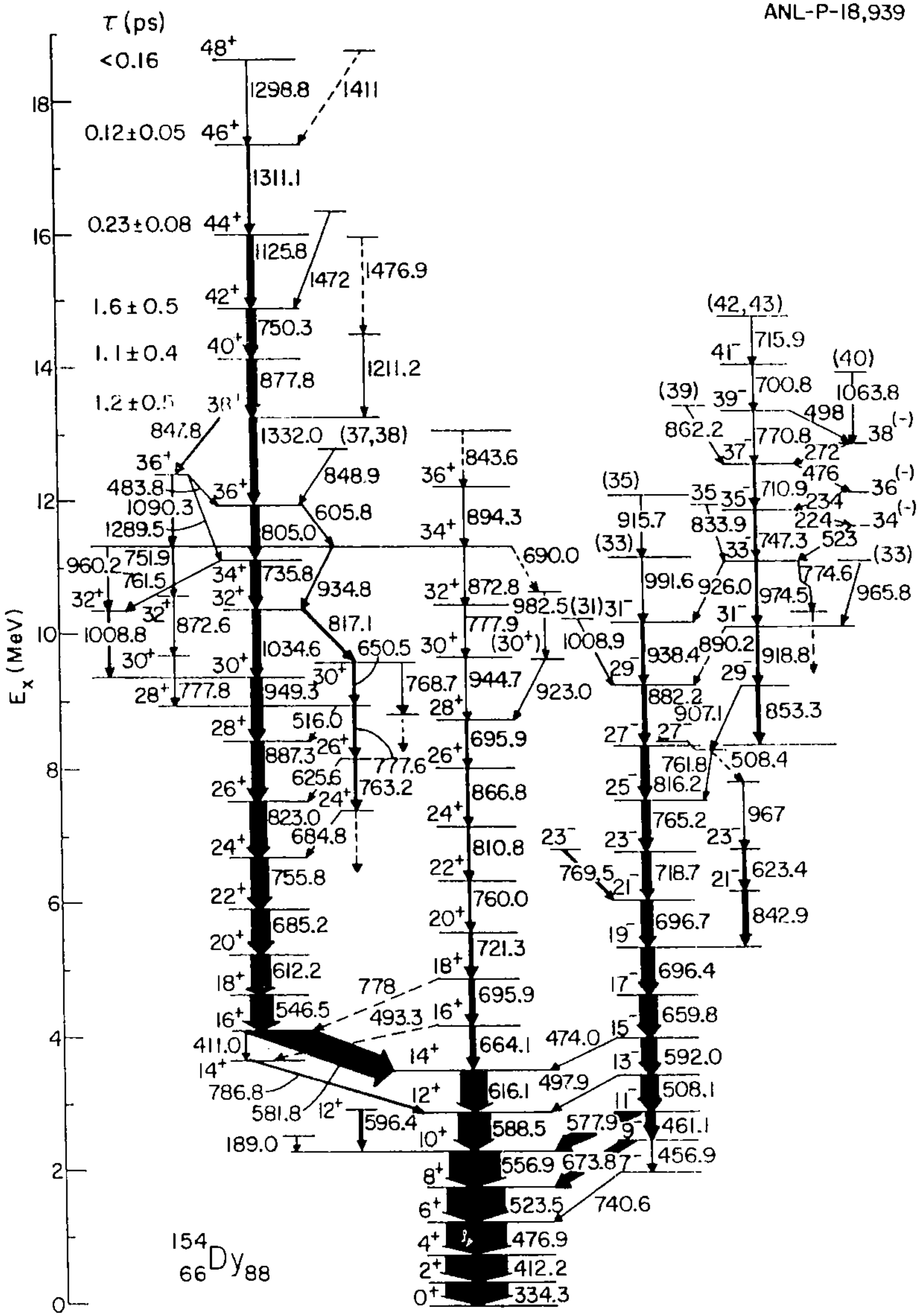

Fig. I-8. ^{154}Dy level scheme. Lifetimes for the higher spin positive parity levels are also given.

the yrast structure exhibits moderate collectivity (Q_o = 198 - 243 e.b.; B(E2) = 29 - 43 W.u.). The observation of several non-yrast levels has also made it possible to see a change of structure with increasing excitation energy above the yrast line, and to follow the descent of oblate aligned-particle configurations towards the yrast line with increasing spin until they cross both the gs and $\nu i_{13/2}$ band. The theoretical predictions in the band-terminating picture impressively account for the observed features for I < 36. The return of collectivity at higher spins was, however, not predicted, thereby raising challenging questions about the nature of collectivity at the highest spins.

The results have been published.[3]

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[3] W. C. Ma et al., Phys. Rev. Lett. 61, 46 (1988).

e. Structural Changes Above the Yrast Lines of $^{154-156}$Dy (T. L. Khoo, I. Ahmad, R. V. F. Janssens, R. Holzmann,* H. Emling,* W. C. Ma,† B. K. Dichter,‡ M. W. Drigert,§ U. Garg,¶ M. A. Quader,‖ P. J. Daly,‖ M. Piiparinen,** and W. Trzaska**)

Hot nuclei provide opportunities to study several aspects of physics. In nuclear structure it is interesting to examine the change of shapes, thermal shape fluctuations, and the melting of shell-effects with increasing temperature. Calculations based on the Landau theory of phase transitions[1] and the finite-temperature Hartree-Fock-Bogoliubov method[2] predict that nuclei which are prolate along the yrast line become triaxial with increasing excitation energy above the yrast line, U, and undergo a phase transition to oblate shape at a critical temperature T_{cr}

To probe nuclear behavior in the U = 1-8 MeV range, we have measured quasicontinuous spectra of γ rays which connect excited states in the region of high level densities. We have found evidence for structural changes in the quasicontinuum states and, perhaps, also for the large fluctuations which are expected near a phase transition.

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The evolution of the γ quasicontinuum spectrum with neutron number has been investigated in the sequence of isotopes $^{152,154,156}Dy$. The three nuclei display a pronounced collective (fast) E2 component. In ^{154}Dy this component splits into two distinct parts, signifying a structural change along the γ cascade above the yrast line. The E2 and statistical components are reproduced in simple γ cascade calculations; in ^{152}Dy and ^{156}Dy only rotational bands are included, whereas in ^{154}Dy additional vibration-like transitions are required to reproduce the two E2 peaks.

The appearance of two broad peaks in ^{154}Dy results from a redistribution of transition energies along the γ de-excitation pathway; in the later decay stage, transition energies are shifted downwards, causing a clustering around 780 keV and a dip around 1.1 MeV. The two peaks provide clear signature for a change in nuclear structure above the yrast line. In ^{152}Dy the collective E2 cascade is similar to that of the first part in ^{154}Dy. However, in ^{152}Dy the collective flow terminates, on average, at U = 1-1.5 MeV and I ~34 $\hbar$, as aligned-particle configurations dominate in the vicinity of the yrast line and dipole transitions emerge. Aligned-particle configurations are not dominant along the yrast line in ^{156}Dy, allowing the E2 cascade to continue to U ~0.7 MeV and I ~26, and this results in a larger E2 multiplicity. Only a single peak is observed, implying rotational behavior with the transition energy decreasing with spin throughout the quasicontinuum cascade.

These conclusions were derived with the aid of Monte Carlo calculations of the γ cascade, which take into account the competition of statistical E1 and collective E2 decay at high excitation energy. The calculations reproduced simultaneously <u>all</u> observed features of the E2 and statistical components, i.e. their multiplicities, spectral shapes, Doppler shifts and entry points into the yrast region. This simple model can reproduce the data for ^{152}Dy and ^{156}Dy but is unable to reproduce the splitting of the E2 component seen in ^{154}Dy. However, by assuming a change from rotational to vibration-like behavior (i.e. transition energies which remain constant with spin) for excitation energy $E^* < 17$ MeV, the observed features at all beam energies could be reproduced with one common set of parameters.

The structural changes in ^{154}Dy are probably connected with variations of the nuclear shape. In this transitional nucleus the shape transition from triaxial to oblate is predicted to occur at low U, even at the yrast line for I $\gtrsim$38 $\hbar$, in fair agreement with an established oblate region for I between 32 and 38 $\hbar$. For all bombarding energies the γ cascades cross the predicted phase transition boundary. The large shape fluctuations expected in the transition region give a potential energy surface flat in the β-γ plane and perhaps vibration-like transitions.

A paper on this work has been published.[3] Future work will focus on extracting more detailed understanding of the structural changes in the excited states of ^{154}Dy. The γ transitions from different regions of spin and excitation energy will be enhanced using a new method we have developed, viz. by selecting different entry points (spins) into the yrast line. In addition, 2-dimensional gamma-gamma matrices will be examined to determine the rotational or vibration-like correlations.

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[3]R. Holzmann et al., Phys. Rev. Lett. 62, 520 (1989).

f. The g-Factor of the 59/2, 1-ns Level in ^{147}Gd (M. Hass, I. Ahmad, R. V. F. Janssens, T. L. Khoo, H.-J. Körner, E. F. Moore, F. H. L. Wolfs, N. Benczer-Koller,* K. Beard,† U. Garg,† E. Daphni,‡ P.J. Daly,§ and M. Piiparinen§)

The experimental determination of magnetic moments has traditionally played an important role in the evolution of nuclear structure since they probe the single-particle degrees of freedom, in contrast to E2 properties which probe collective features.

The g-factor of the 59/2, 1-ns level in ^{147}Gd has been determined by the transient-field method for ions recoiling through the magnetized Gd foil at a temperature of 100 degrees K. The ^{76}Ge(^{76}Ge,5n) reaction at 310 MeV was used to provide high-recoil velocity. The experiment was performed with the Argonne-Notre Dame γ-ray facility. A flight distance in vacuum between the target and

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the ferromagnet corresponding to 100 ps ensured that the γ-ray cascades fed the 59/2 level before the ions traversed the Gd foil. Clean channel selection of the ^{147}Gd
nuclei was achieved by requiring (i) a high-prompt multiplicity in the BGO array as well as (ii) a high-delayed multiplicity (a 49/2, 500-ns isomer is present in the nucleus). The g-factor was extracted from standard double-ratios with the known parametrization of the transient field, yielding g = 0.38(7). Results with less statistical significance were also obtained for levels in ^{146,148}Gd. The measured value for the g-factor of the 59/2 state was compared with the ones expected for the proposed wave function. The latter is composed of a $\nu(f_{7/2}h_{9/2}i_{13/2})$ neutron single-particle part and either a $\pi(g^{-1}{}_{7/2}h^{3}{}_{11/2})$ or a $\pi(d^{-1}{}_{5/2}h^{3}{}_{11/2})$ part. The resulting g-factors, based on experimental single-particle g-factors in this mass region, are g = +0.43 and +0.51, respectively. Our result would indicate a preference for the $g_{7/2}$ proton-hole in the wave function and certainly indicates that the basic components of the suggested wave function are correct.

The present result can be viewed as a significant step towards future g-factor determination in this nucleus, where the relative proton-neutron contribution to the total spin would be probed in the vicinity of the yrast line at even higher spin. By varying the flight distance between the target and the ferromagnet, one can control the population of levels experiencing the transient field, without any change in the other experimental conditions. Measurements along these lines are planned in the near future.

g. Octupole Deformation Near Z = 56, N = 88 (R. V. F. Janssens, I. Ahmad, T. L. Khoo, M. W. Drigert,* and W. R. Phillips†)

The analysis of a γ-γ coincidence experiment performed with a ^{252}Cf fission source at the Argonne-Notre Dame BGO γ-ray facility has continued. The aim of this experiment was to study the level structures of neutron-rich fission fragments which cannot be studied with the conventional in-beam techniques. From these studies we deduced that octupole deformation occurs in the ^{144,146}Ba nuclei. Partial decay schemes for the very neutron-rich ^{146,148,150}Ce nuclei have now been determined from analysis performed at Manchester. Similar behavior to that seen in ^{144,146}Ba and interpreted in terms of strong octupole correlations, has been observed in the yrast levels of ^{146}Ce but not in ^{148}Ce and ^{150}Ce. This result is in agreement with the predictions of cranked mean-field calculations which emphasize the importance of the N = 88 neutrons in this context. The intrinsic dipole moments in the N = 88 nuclei deduced from our data are reproduced rather well in these calculations. For example, the measured intrinsic dipole moment for ^{146}Ce is 0.20 efm. which compares well with the calculated value of 0.18 efm.

A paper reporting these results has been published.[1] Experiments are planned with a ^{254}Cf source in order to study in detail some nuclei with a larger neutron excess than those discussed above. These data should also allow us to study the odd-even Ce and Ba isotopes in detail. For the study of the latter isotopes, the current data set has too limited statistical accuracy.

[1]W. R. Phillips et al., Phys. Lett. B212, 402 (1988).

h. Complex Band Structure in ^{219}Ac (R. V. F. Janssens, I. Ahmad, T. L. Khoo, M. W. Drigert,* W. Trzaska,† and J. Cizewski,‡)

The nucleus ^{219}Ac is located at the border of the region where stable octupole deformation has been reported. Early studies of this nucleus have indicated a rich band structure. In particular, alternating positive- and negative-parity bands connected by strong E1 transitions were seen.

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The aim of this experiment is to take advantage of the power of the Argonne-Notre Dame gamma-ray facility to extend our knowledge of this nucleus as much as possible.

The analysis of a γ-γ coincidence experiment and a conversion electron measurement performed last year has continued at I.N.E.L. The data are rather complex. In particular a large number of low-energy transitions are present in the spectra, which are rather difficult to disentangle and place in a coherent level scheme. Nevertheless, the level scheme has been extended towards higher spins and new level sequences have been observed. The analysis is continuing at I.N.E.L. and experiments on neighboring nuclei are planned in the near future.

i. Investigation of Octupole-Deformed Th Nuclei (I. Ahmad, R. V. F. Janssens, T. L. Khoo, H.-J. Körner, E. F. Moore, G.-E. Rathke, F. L. H. Wolfs, D. Habs,* and M. W. Drigert†)

During the last few years a wealth of spectroscopic data has been accumulated on neutron-deficient Ra and Th nuclei, showing that they are reflection asymmetric. In particular, the most recent level scheme for ^{223}Th shows that a sequence of parity doublets has been traced for the first time up to very high spins.[1] In the neighboring ^{222}Th nucleus the alternating sequence of positive- and negative-parity states has been followed up into a region where band crossings occur. The aim of the present experiment was to extend these studies to the lighter ^{221,220}Th nuclei in order to (i) identify similar band structures, (ii) study signature and parity splitting as a function of spin more systematically and (iii) confirm that the alternating sequence of positive- and negative-parity states in ^{220}Th does not continue beyond the first backbend.

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[1]D. Habs et al., Proceedings of Conference on High Spin Nuclear Structure and Novel Nuclear Shapes, Argonne (1988), ANL-PHY-88-2, p. 121.

The experiment was performed with the Argonne-Notre Dame BGO gamma-ray facility coupled with the Heidelberg electrostatic separator. The latter instrument is used to separate the evaporation residues from the fission fragments which are also copiously produced. A γ-γ-recoil coincidence measurement was performed with the $^{208}Pb(^{16}O,xn)$ reaction at ATLAS energies varying between 75 and 85 MeV. The data are currently under analysis in Heidelberg. Depending on the results, experiments on other nuclei in this mass region will be planned.

j. <u>Identification of High-j States in Actinide Nuclei</u> (I. Ahmad, R. V. F. Janssens, E. F. Moore, K. E. Rehm, and T. F. Wang)

High-j single-particle states in ^{238}U and ^{232}Th have been investigated by $(^{16}O,^{15}O)$ transfer reaction. It has been shown previously that $(^{16}O,^{15}O)$ reaction preferentially populates high angular-momentum states in the rare-earth nuclei. The interest in high-j states, in particular the $k_{17/2}$ shell state in ^{249}Cm, arises because the location of this state will provide the gap parameter at N = 184 which is responsible for the stability of superheavy elements. The feasibility of this reaction was checked with ^{238}U and ^{232}Th targets. Targets of 300-mg/cm^2 ^{232}Th and ^{238}U were exposed to 150-MeV ^{16}O ions and the resulting ^{15}O ions were identified with a position-sensitive gas detector placed in the focal plane of an Enge split-pole magnetic spectrograph. In the case of ^{232}Th, we identified the known I = 15/2 member of the ground-state band in ^{233}Th with a cross section of ~ 1 mb/sr. In addition, several excited states were observed in both ^{233}Th and ^{238}U. However, without the measurement of the de-exciting gamma rays it is not possible to identify these states.

An attempt was made to measure gamma rays in coincidence with ^{15}O ions. It was found that gamma rays from the Faraday cup were about 3 times more intense than the gamma-rays produced in the target. A 20% Ge and a LEPS detector were used in the experiment. In a short run we could not see any gamma ray in the LEPS detector. A better design of the Faraday cup and the use of Gated Integrated Amplifiers (which can handle high counting rates) will make particle-gamma measurements possible.

k. Spectroscopy of ^{221}Pa (I. Ahmad, R. Holzmann, R. V. F. Janssens, T. L. Khoo, F. Moore, F. L. H. Wolfs, W. C. Ma,* M. Drigert,† D. Habs‡ and J. A. Cizewski§)

Several attempts were made to produce ^{221}Pa ($T_{1/2}$ ~ 6 μs) by ^{209}Bi (^{16}O,4n) reaction. This nucleus has so far been identified only in a recoil mass separator. The eventual aim of the experiment was to study the level structure of ^{221}Pa. In one experiment a 1-mg/cm^2 ^{209}Bi target was bombarded with 94-MeV ^{16}O ions and alpha particles emitted during a 20 μs period after the beam bursts were detected in a silicon detector placed at 135 degrees with respect to the beam direction. We observed alpha particles associated with the decays of francium (Z = 87) and actinium (Z = 89) isotopes but did not observe any α decays of Pa nuclei. In another experiment, a 300-μg/cm^2 ^{209}Bi target was irradiated with a 94-MeV ^{16}O beam and the recoiling nuclei were stopped in an aluminum foil with a hole for the passage of the beam. Again we observed Fr and Ac nuclei but no Pa isotopes.

In a third attempt we used an electrostatic deflector to deflect the reaction products away from the beam. We did not see any alpha activity above the background produced by the residual beam. In all these experiments beam energies were varied from 82 to 100 MeV. These three measurements indicate extremely low cross section (< 100 μb) for the production of ^{221}Pa. Very low cross sections (~ 10 μb) for the production of ^{219}Pa and ^{220}Pa have recently been reported at GSI. It should be remarked that the cross sections for the production of Ac and Th nuclei by similar fusion reactions are several millibarns. Thus we see a drastic reduction in the fusion cross section for Pa and heavier nuclei. We plan to use the high sensitivity of the Fragment Mass Analyzer to identify ^{221}Pa nuclides.

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ℓ. Octupole Deformation in ^{223}Ac (I. Ahmad, R. V. F. Janssens, R. Holzmann,* M. Huyse,† P. Dendooven,† P. Van Duppen,† and G. A. Leander‡)

The level structure of ^{223}Ac has been studied with the aim of understanding the presence of octupole deformation in the mass-220 region. Our experiments in the past have established octupole deformation in the ground states of ^{225}Ac and ^{229}Pa. In ^{225}Ac several interesting features were observed, all of which support the concept of reflection asymmetric shape for its ground state. Recent calculations indicate that ^{221}Ac and ^{223}Ac should have larger octupole deformation than that in ^{225}Ac. For this reason two experiments were performed at the Leuven-la-Neuve (Belgium) cyclotron using the recently-developed ion-guide technique. The ^{227}Pa sources were produced by the bombardment of a 6-mg/cm^2 ^{232}Th target with 55-MeV protons and were mass separated. Alpha singles, alpha-gamma and alpha-electron coincidences and level lifetimes were measured. The analysis of the data confirms the previous tentative assignments of the $5/2^+$ and $5/2^-$ bands. A level scheme for ^{223}Ac is shown in Fig. I-9. The 50- and 107-keV levels have been assigned to the 5/2 and 7/2 members of the $3/2^-$ band. The level spacings and alpha intensities indicate small Coriolis interaction matrix elements, similar to that seen in ^{225}Ac. The lifetime of the 65-keV level has been measured to be < 250 ps which corresponds to a B(E1) value of > 0.003 W.u. for the $5/2^+ \rightarrow 5/2^-$ transition. Both the reduction in the Coriolis matrix elements and fast E1 transitions clearly indicate a reflection asymmetric shape for ^{223}Ac ground state.

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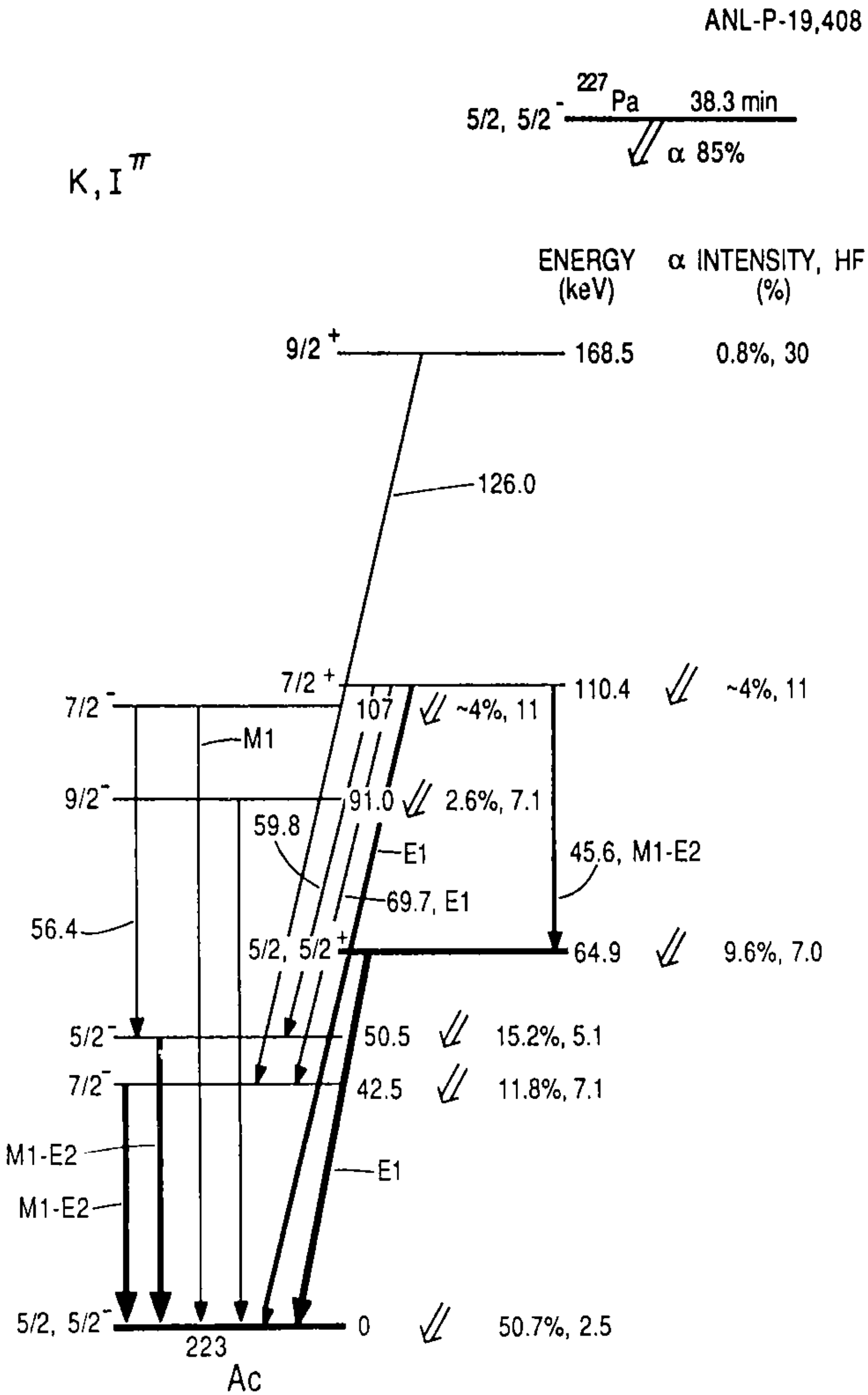

Fig. I-9. Level scheme for ^{223}Ac deduced from the alpha decay of ^{227}Pa.

m. <u>Proton-Rich Shell-Model Nuclei with N ≃ 82</u> (R. V. F. Janssens, I. Ahmad, T. L. Khoo, R. Holzmann,* W. C. Ma,† R. Broda,‡ M. Quader,‡ P. J. Daly,‡ Z. W. Grabowski,‡ W. Trzaska,‡ and M. W. Drigert§)

It is well established by now that the low-energy level spectra of $Z \geq 64$ nuclei with N = 82 may be described in terms of shell-model configurations involving the few valence nucleons outside the ^{146}Gd core. Over several years a collaboration led by the Purdue group has performed at Argonne the first studies of some twelve N = 81, 82, 83 nuclei close to the proton drip line. We have found in general that the observed level spectra and transition probabilities can be quantitatively explained in a consistent shell-model treatment using empirical residual interactions and effective charges. The E2 transition rates between $\pi h_{11/2}$ states in the N = 82 isotones decline sharply with increasing Z (approaching the half-filled $\pi h_{11/2}$ subshell), and this decline is echoed faithfully in both the N = 81 and N = 83 isotones. At Z = 70 Yb, the $\pi h_{11/2}$ subshell is close to being half filled.

Up to now, our knowledge of the N = 81, 82, 83 spectra is by and large limited to states of modest spin involving the valence particles and simple particle-hole excitations. The next major step is to explore higher-spin reaches of the level spectra to establish when and how configurations involving breaking of the N = 82 core become yrast. With this in mind, we recently performed a full-scale experiment using the Compton-suppressed Ge array and the reaction ^{92}Mo + 250-MeV ^{60}Ni forming the compound nucleus ^{152}Yb. The strongest exit channels were 2p to ^{150}Er and 3p to ^{149} Ho, and very high-quality $\gamma\gamma$ coincidence data, both prompt and delayed, were acquired. Subsequently, the level schemes and ^{150}Er have been considerably extended in analysis performed at Purdue. For example, in ^{150}Er 47 levels accommodating more than 100 transitions have been established between the $(\pi h_{11/2}{}^2)10^+$ isomer at 2.8 MeV and a 43 ns isomer at 9.5 MeV. We are currently working on interpreting the results for both nuclei in terms of specific shell-model configurations. Our other active project of this kind concerns the

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odd-odd N=81 nuclei ^{146}Tb, ^{148}Ho and and ^{150}Tm. In each of these isotones we have identified a $(\pi h_{11/2}\nu h_{11/2}^{-1})10^{+}$ millisecond isomer that decays by a retarded E3 transition to a $(\pi h_{11/2}\nu d_{3/2}^{-1})7^{-}$ state that de-excites to other members of $\pi h_{11/2}\nu d_{3/2}^{-1}$ and $\pi h_{11/2}\nu s_{1/2}^{-1}$ multiplets. All the observed transitions have been firmly placed in the three-level schemes. We are now working with R. D. Lawson on their interpretation using Schiffer-True and other formulations for the proton-neutron hole residual interactions.

n. Investigation of Shape Coexistence in ^{182}Hg (I. Ahmad, R. V. F. Janssens, E. F. Moore, A. K. Ramayya,* J. Kormicki,* A. Bavishi,* Z. W. Grabowski,† and W. Trzaska†)

The discovery of the well-developed rotational bands, built on the excited 0_2^+ state, in the lighter Hg isotopes (A < 188) was rather unexpected since the proton number (Z = 80) is very close to the closed Z = 82 shell. Soon it was established experimentally that the excitation energy of the 0_2^+ band head of the deformed band is decreasing rapidly with decreasing neutron number N. Thus it is of interest to determine if this state may become the ground state in the lighter Hg isotopes.

From recent work by W. C. Ma et al.[1] the energy of the levels in the deformed band in ^{182}Hg have been established for spins between 6^+ and 12^+. The energy of the unobserved 0_2^+ band head was extrapolated to be 338 keV. This energy could be slightly higher if one takes into account the repulsion of the ground state. The exact location in energy of this state is important since several calculations which attempt to describe the shape of these Hg nuclei give conflicting predictions for the variation of the excitation energy of the 0_2^+ band head as a function of N. The latest calculations by the Lund group, for example, predict that the prolate band never becomes yrast and has the smallest energy difference with the oblate ground state at N = 104.

We have measured directly the energy of the 0_2^+ - 0_1^+ E0 transition using the Purdue-Argonne superconducting electron spectrometer. The reaction ^{154}Gd(^{32}S,4n) was used with a beam energy of 160 MeV. In a configuration chosen to minimize the Doppler broadening of the electron lines, only electrons emitted at 90 ± 7.5 degrees with respect to the beam axis were accepted. The electron-gamma coincidence events were also recorded.

[1]W. C. Ma et al., Phys. Lett. B167, 277 (1986).

The preliminary results give an electron line at 306 keV with no corresponding gamma transition. This yields a value of 388 keV for the excitation energy of the 0_2^+ state in ^{182}Hg which indicates that the excitation energy of the prolate band is higher in this case than in ^{184}Hg (375 keV). This finding is in qualitative agreement with the recent Lund calculations. It should be pointed out, however, that our result involves a rather large correction for the removal of a contaminant line attributed to a transition due to Coulomb excitation of the Gd target. At present this correction is not fully worked out. We are planning another experiment where the need for this correction will be eliminated by the use of another projectile-target combination.

o. Strong Nuclear Structure Dependence of Heavy-Ion Fusion Partial-Wave Distributions (R. V. F. Janssens, T. L. Khoo, W. Kühn,* A. Ruckelshausen,* R. D. Fisher,* G. Breitbach,* H. J. Hennrich,* V. Metag,* R. Novotny,* D. Habs,†, D. Schwalm,† B. Haas,‡ and R. S. Simon§)

The discovery of enhanced sub-barrier fusion cross sections and its subsequent interpretation in terms of coupling to binary reaction channels has renewed the interest in near-barrier heavy-ion fusion studies. The knowledge of the compound-nucleus angular-momentum distribution is of crucial importance for an understanding of the fusion process in the barrier region. Recently, new techniques involving 4π γ detector systems have been developed which allow for a direct measurement of the angular momentum distribution of fusion products.

Partial-wave cross sections for fusion of ^{64}Ni + ^{92}Zr and ^{64}Ni + ^{96}Zr at energies of 5% and 7% above the Bass-model fusion barrier have been measured with the Darmstadt-Heidelberg Crystal Ball. The distribution for fusion with the more neutron-deficient target ^{92}Zr exhausts the unitarity limit for lower angular momenta. In contrast, fusion with the slightly more neutron-rich target, ^{96}Zr, yields a broad angular-momentum distribution with cross sections well below unitarity even for small partial waves (see Fig. I-10). At the moment, no detailed explanation for this effect is available. However, one can speculate that since the entrance-channel mass asymmetry and the

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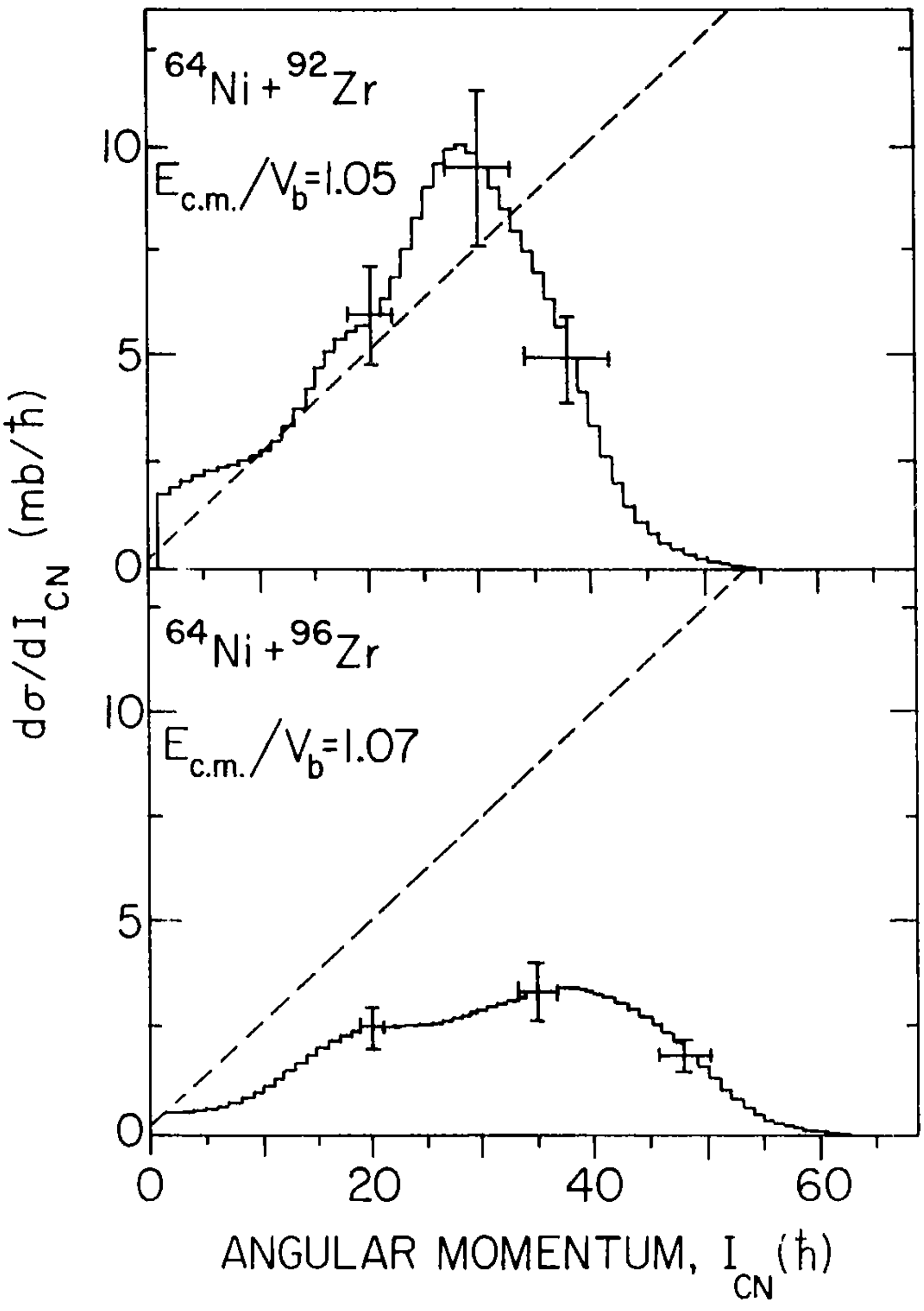

Fig. I-10. Compound nucleus angular momentum distributions (solid histograms) for $^{64}Ni + ^{92}Zr \rightarrow ^{156}Er$ (top) and $^{64}Ni + ^{96}Zr \rightarrow ^{160}Er$ (bottom). The dashed histograms indicate the experimental uncertainties. The dashed straight lines show the partial wave cross sections given by the unitarity limit.

incident energy are almost identical for both systems, the observed differences might be due to an increase in the effective fusion barrier caused by changes in nuclear structure with increasing neutron number. A paper reporting these results has been submitted for publication.

p. Charged-Particle Gamma-Ray Coincidences as Probe of Nuclear Structure at High Spin (R. R. Betts, T. F. Wang, F. L. H. Wolfs, R. V. F. Janssens, S. J. Sanders, and T. L. Khoo)

In an attempt to gain information on the shapes of hot high spin nuclei we have studied the spectra of charged particles emitted from compound nuclei formed in heavy-ion fusion reactions. The experiments were performed using a number of charged-particle detectors placed in the center of the Argonne-Notre Dame BGO-CSS array. Alpha particles and protons were detected in coincidence with discrete gamma rays from the evaporation residues thus uniquely identifying the decay channels from which the charged particles originate. The major qualitative result of this work is that differences are observed in the spectra measured at different angles. This result can be related in a quantitative way to the effects of deformation of the emitting system and the alignment of the compound nucleus angular momentum produced in fusion.

To date we have studied three systems, $^{64}Ni + ^{92}Zr \rightarrow ^{156}Er^*$, $^{12}C + ^{144}Sm \rightarrow ^{156}Er^*$ and $^{16}O + ^{154}Sm \rightarrow ^{170}Yb^*$. The first two reactions populate the same compound nucleus in similar regions of excitation energy, although the angular momentum in the first is larger. The $^{64}Ni + ^{92}Zr$ reaction leads to alpha particle and proton spectra which show pronounced deformation effects whereas the $^{12}C + ^{144}Sm$ data show none. This result is inconsistent with the usual compound-nucleus hypothesis which requires decay independent of formation. These data further suggest, consistent with earlier speculations, that the decaying system formed via $^{64}Ni + ^{92}Zr$ is indeed extremely deformed.

The $^{16}O + ^{154}Sm$ data show moderate deformation effects, consistent with earlier results on charged-particle anisotropies.

Our future plans include measurements of Sn compound nuclei, known from giant-resonance work to be spherical in the relevant region of excitation energy and spin.

D. ACCELERATOR MASS SPECTROMETRY (AMS)

In the last year, the AMS program at ATLAS was focussed on further exploring the radiocalcium dating method utilizing the cosmogenic radioisotope ^{41}Ca ($t_{1/2} = 1.0 \times 10^5$ yr). This project takes advantage of the ATLAS system which provides a perfect isotopic filter through the velocity-dependent rf structure of the linac, and boosts the energy of the ions to a level where an excellent isobaric separation with the newly-developed method of a gas-filled magnetic spectrograph can be achieved.

Radiocalcium was proposed many years ago as a potential candidate for dating fossil bones in the range of 0.1 to 1 million years, thus extending the time range accessible to radiocarbon dating ($\lesssim$ 50,000 years) by more than one order of magnitude. In 1986 we detected[1] for the first time ^{41}Ca in a contemporary cow bone at a level of $^{41}Ca/Ca = 2.0 \times 10^{-14}$. However, this was only possible with the help of an elaborate isotopic enrichment process prior to the AMS measurement. Efforts to improve the efficiency of the AMS method to a level where the extremely low ^{41}Ca concentrations can be measured directly with AMS were started in 1987. In the past year we succeeded in measuring natural terrestrial ^{41}Ca contents in bones and minerals without the need of pre-enrichment.

With the advent of the new positive-ion injector of ATLAS, new possibilities for AMS emerge. It is expected that it will lead to a further substantial improvement of ^{41}Ca detection compared to the tandem-based system. In addition, ideas are being developed for AMS of noble gas radioisotopes.

A first experiment to suppress stable isobar interferences in AMS measurements by selective ion interaction with negative ions was performed at the Rehovot tandem accelerator facility, resulting in a proof-of-principle of this new method.

[1] W. Henning et al., Science 236, 725 (1987).

a. Development of an Intense CaH_3^- Beam for ^{41}Ca Detection at Natural Terrestrial Levels (W. Kutschera and M. Paul*)

Recently, P. Sharma and R. Middleton[1] from the University of Pennsylvania reported $^{40}CaH_3^-$ beams of several microamps produced with a high-intensity cesium sputter source using CaH_2 as source material. Although the use of CaH_2 imposes substantial preparatory problems because of the reactivity of the material, the advantages for a very sensitive ^{41}Ca detection are outstanding. The overriding problem in AMS measurements is the interference from the stable isobar. Since $^{41}KH_3$ does not form stable negative ions, the use of $^{41}CaH_3^-$ ions greatly suppresses the otherwise overwhelming interference of ^{41}K. With a new second-generation sputter source purchased from NEC (called SNICS II) we were able to produce $^{40}CaH_3^-$ beams of one to two microamps from CaH_2 material prepared from "real" samples. This then allowed us to attempt direct $^{41}Ca/Ca$ ratio measurements at ATLAS. For the CaH_2 preparation, typically 50 mg of CaO were converted to CaH_2 by first reducing the oxide to Ca metal with Zr and then hydrogenating it by heating in an H_2 atmosphere. The resulting CaH_2 is highly reactive and has to be stored in vacuum or Ar atmosphere until it is mounted in the ion source.

*Racah Institute of Physics, Hebrew University, Jerusalem, Israel.
[1]P. Sharma and R. Middleton, Nucl. Instrum. Methods B29, 63 (1987).

b. Measurements of $^{41}Ca/Ca$ Ratios in Natural Calcium Materials
(W. Kutschera, I. Ahmad, P. J. Billquist, B. G. Glagola, K. Furer, R. C. Pardo, K. E. Rehm, J. L. Yntema, M. Paul*, P. J. Slota† and R. E. Taylor†)

One of the basic tasks in developing a ^{41}Ca dating method is to establish the global ^{41}Ca distribution on Earth. In contrast to ^{14}C, the main production of ^{41}Ca does not occur in the atmosphere but in the lithosphere near the surface of the Earth through capture of cosmic-ray secondary neutrons in ^{40}Ca. The pathways of ^{41}Ca from the lithosphere (rocks) via the hydrosphere (erosion) into the biosphere (uptake by plants, animals and humans) are complex and therefore difficult to predict quantitatively. Local variations are likely to occur on a short time scale. However, it may not be unreasonable to assume that the long half-life of ^{41}Ca ($t_{1/2}$ = 100,000 years) will help to attenuate these variations.

The first round of experiments last year on several bone samples (both animal and human) and limestone materials revealed[1] the following situation:

(i) In general, the $^{41}Ca/Ca$ ratios lie in the range from 10^{-15} to 10^{-14}, reasonably close to the estimated equilibrium abundance near the surface. Figure I-11 shows mass-41 spectra measured for a calibration and a human bone sample in the gas-filled spectrograph.

(ii) The modern cow bone value of 2×10^{-14} previously measured with pre-enriched material was confirmed by the direct AMS measurement.

(iii) However, the uncertainty of the measured values is at present too large to obtain reliable information on the distribution of natural ^{41}Ca.

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†Department of Anthropology, University of California, Riverside, CA.
[1]W. Kutschera et al., Proc. 13th Int. Radiocarbon Conference, Dubrovnik, Yugoslavia, June 20-25, 1988, to be published in Radiocarbon.

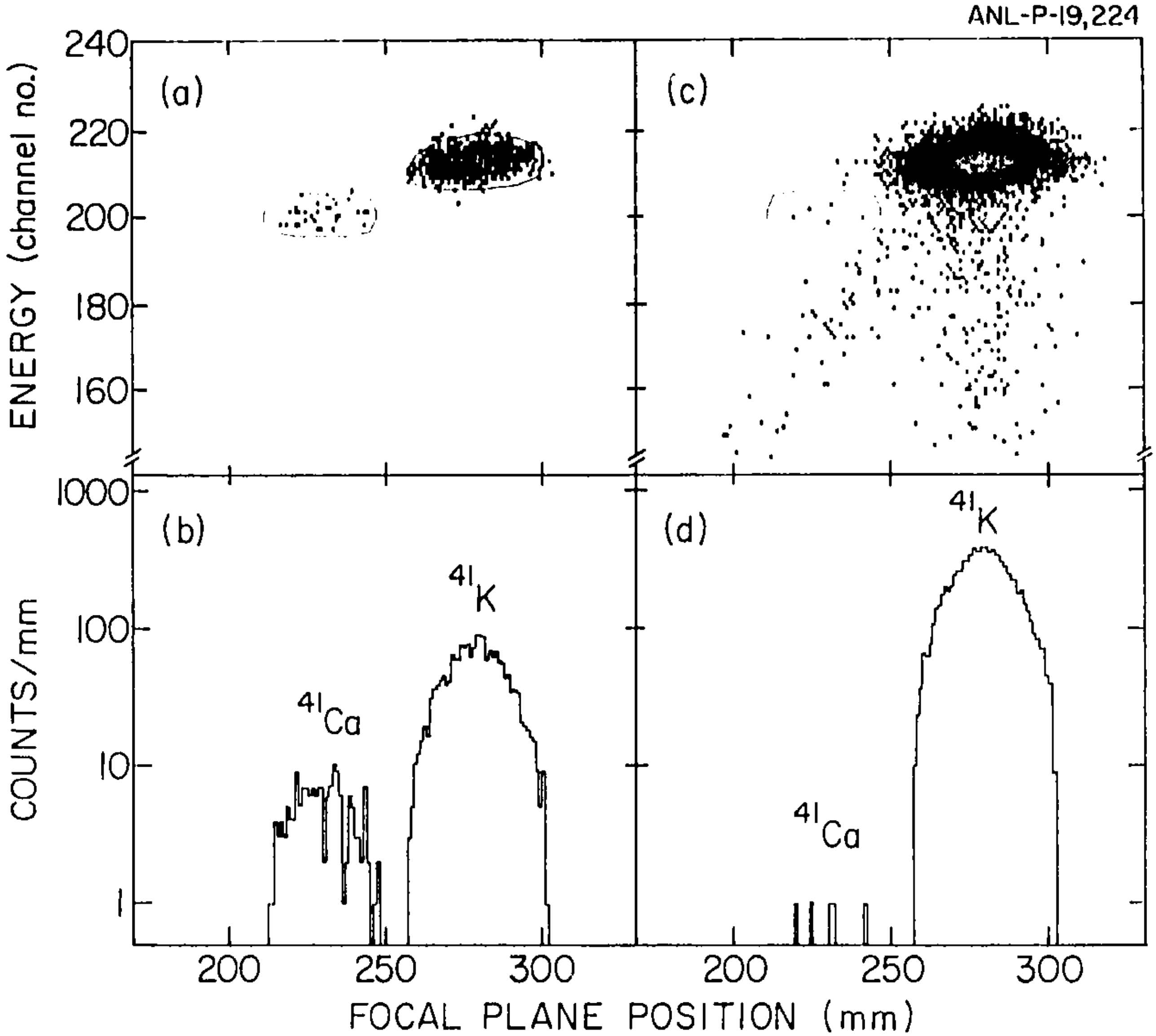

Fig. I-11. Mass-41 spectra measured in the gas-filled magnetic spectrograph from a calibration sample (a,b) with $^{41}Ca/Ca = 1.44 \times 10^{-12}$ and from a 2,740-yr-old homosapiens bone (c,d) with $^{41}Ca/Ca = 1.2 \times 10^{-14}$. The upper two spectra show two-dimensional scatter plots of focal-plane position versus energy. To set the mass-41 windows cleanly, one-count events are not shown in spectrum (a). On the contrary, all counts are shown in figure (c). All events contained within the windows (set identical for both samples) are projected onto the position axis in figures (b) and (d), respectively. The five ^{41}Ca events for the bone sample were collected in 116 min of running time, with a $^{40}CaH_3^-$ beam current of 0.9 μA.

(iv) To meet this goal a substantial increase in overall detection efficiency and the use of a simpler source material is required. This is important to obtain statistically significant results and to avoid possible contamination with highly-enriched material used to prepare calibration samples.

An improvement over the present AMS system is expected from the ECR-PII (Electron Cyclotron Resonance source - Positive Ion Injector) of ATLAS which is nearing completion. The use of CaO rather than the reactive CaH_2 as source material, combined with a strong beam of highly-charged Ca ions and a good overall detection efficiency, could lead to an improvement of up to a factor 100 over the present tandem-based AMS system. Optimistically, a ^{41}Ca counting rate of 10 per minute can be expected for a ^{41}Ca/Ca ratio of 10^{-14}. This would then allow us to perform the systematic measurements necessary to explore the ^{41}Ca abundance on Earth. Since the isobaric background of ^{41}K is expected to be much stronger than with negative-ion injection, isobar separation by fully stripping will be employed. At 400- to 450-MeV energy approximately 50% of the ^{41}Ca ions can be stripped into the 20+ charge state and cleanly separated from ^{41}K which cannot acquire a charge higher than 19+.

c. The Half-Life of ^{41}Ca (I. Ahmad, W. Kutschera and M. Paul*)

A trivial condition to use a radioisotope for dating is to know its half-life. Despite a fairly precise half-life value of ^{41}Ca reported[1] in the literature, $t_{1/2}$ = (1.03 ± 0.04) x 10^5 years, it is generally believed that the half-life is still uncertain by about 30%. The main reason is that so far no specific activity measurement combined with a mass-spectrometric determination of the ^{41}Ca abundance has been performed. Mabuchi's measurement and two other previous ones determined the ^{41}Ca abundance indirectly from the ^{40}Ca(n,γ)^{41}Ca production rate during neutron irradiation of a calcium sample in a reactor.

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[1]H. Mabuchi et al., J. Inorg. Nucl. Chem. 36, 1687 (1974).

We have started a new half-life measurement with the goal to overcome the shortcomings of the previous measurements and to reach a "realistic" accuracy of at least 10%. The abundance of calcium isotopes in a highly-enriched material purchased in 1982 from Oak Ridge was measured mass-spectrometrically at Argonne and independently at CalTech, with a consistent result of 1.23% for the ^{41}Ca abundance. The more difficult part is the activity measurement, because ^{41}Ca decays to ^{41}K with a pure electron capture, leaving the K X-rays of 3.3 KeV as the only useful radiation (see Fig. I-12). Preliminary measurements with a Si(Li) X-ray detector indicate that the half-life lies somewhere between 110,000 and 150,000 years. A good activity value requires a careful calibration with X-ray standards to correct for self-absorption effects in the source and to establish the total X-ray detection efficiency. The determination of the ^{41}Ca EC decay rate requires the knowledge of the X-ray fluorescence yield, which is known theoretically to within about 5%.

d. Development of AMS with Noble Gas Radioisotopes using the ECR-PII
(W. Kutschera, I. Ahmad, P. J. Billquist, B. G. Glagola, R. C. Pardo, K. E. Rehm and M. Paul*)

AMS experiments are almost exclusively performed with tandem accelerators. This has obvious advantages for the measurement of long-lived radioisotopes for which the stable isobars do not form negative ions. Examples are ^{14}C, ^{26}Al and ^{129}I, where isobaric interference is avoided through the instability of $^{14}N^-$, $^{26}Mg^-$ and $^{129}Xe^-$ ions. In some cases molecular ions can be utilized, as is done in AMS experiments with ^{41}Ca described above, where the use of $^{41}CaH_3^-$ ions effectively reduces ^{41}K interference through the instability of $^{41}KH_3^-$. Since noble gases do not form stable negative ions, they cannot be investigated at tandem accelerators. On the other hand, there is great interest to use these radioisotopes in geoscience and other fields (including solar-neutrino experiments and searches for the possible existence of strange matter). The primary reason is the chemical inertness of noble gases which leads to a much better understanding of their global distribution than those of reactive elements. They also allow the convenient extraction of the extremely small number of atoms produced in multi-ton solar-neutrino detectors (e.g., about twenty ^{37}Ar atoms are extracted from 600 tons of C_2Cl_4 in the Davis experiment).

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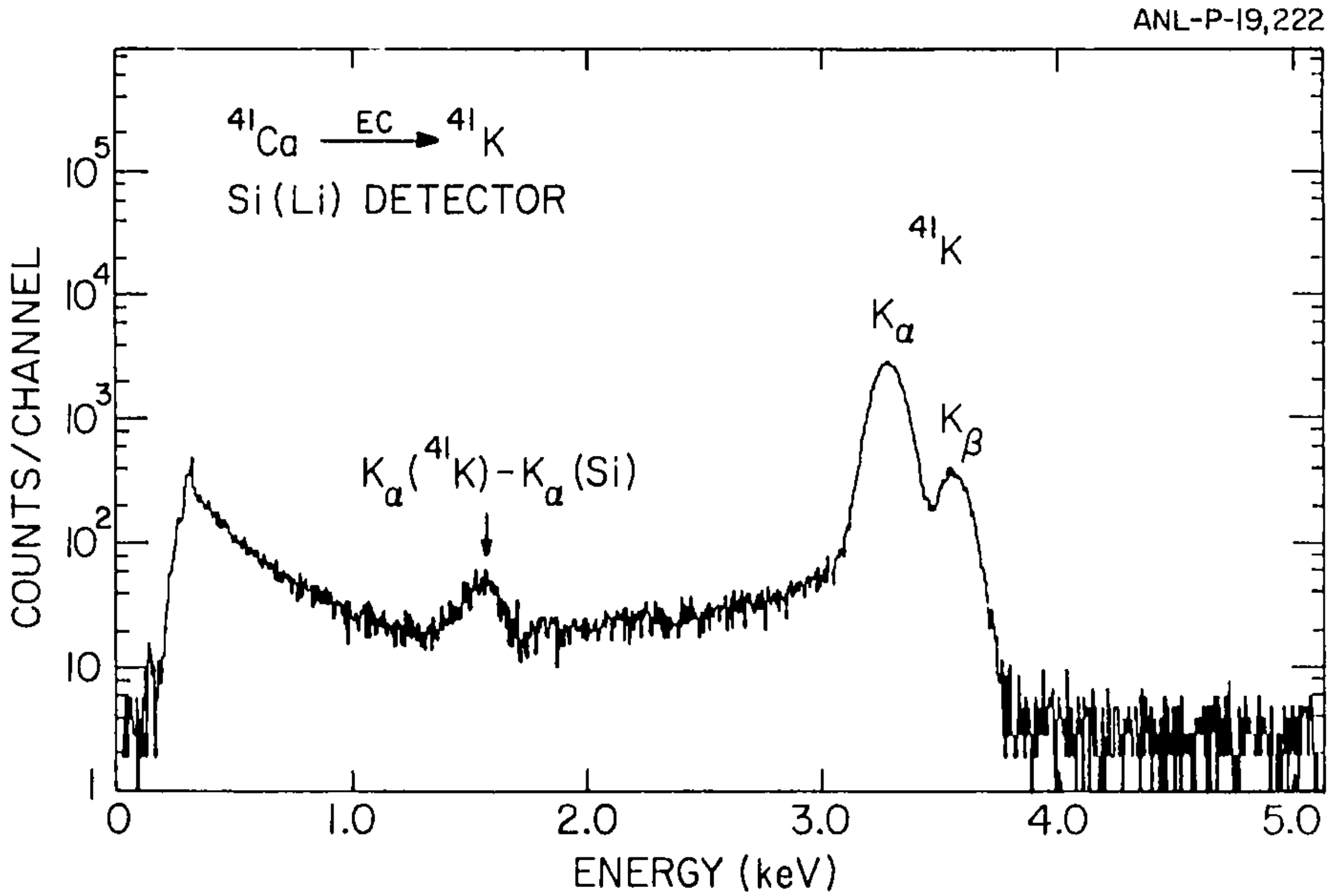

Fig. I-12. X-ray spectrum from the electron capture decay of ^{41}Ca measured in a 6-mm diameter x 5-mm thick Si(Li) detector. The source consisted of 54-μg Ca with an isotopic abundance of 1.23% ^{41}Ca. At a distance of 15-mm, a K X-ray counting rate of 1.76 counts/sec was observed. The peak at 1.65 keV is the result of the escape of the Si K_α X-rays from the detector.

There are three long-lived noble-gas radioisotopes which are potential candidates for AMS: ^{39}Ar, $t_{1/2}$ = 269 yr, isotopic abundance in the atmosphere = 8.1×10^{-16}; ^{81}Kr, 2×10^5 yr, 5.3×10^{-13}; ^{85}Kr, 10.7 yr, 1.3×10^{-11} (1984) and 3×10^{-18} (pre-bomb). The large present-day content of ^{85}Kr is due to releases from nuclear fuel reprocessing. With AMS this may allow one to follow its distribution into natural reservoirs (e.g., groundwater) to very low levels. The most sought application[1] of ^{81}Kr is its measurement in old ice from Greenland and Antarctica. From a geochemical point of view, ^{81}Kr would be an ideal tracer being well mixed in the atmospheric Krypton reservoir, which is of constant size and has essentially no sources or sinks. The low isotopic abundance of ^{39}Ar presents a challenge to the sensitivity of AMS and it has to be seen whether the excellent noble gas performance of ECR sources in connection with ATLAS and our gas-filled magnet-detection technique will make it possible to measure $^{39}Ar/Ar$ ratios in the 10^{-16} range.

[1]H. Oeschger, Nucl. Instrum. Methods B29, 196 (1987).

e. Selective Suppression of Negative Ions by Lasers
(D. Berkovits,* E. Boaretto,* G. Hollos,† W. Kutschera, R. Naaman,† M. Paul,* and Z. Vager)

One of the main tasks in AMS measurements of long-lived radioisotopes is the separation from stable isobar interferences. A first experiment to investigate a new method to suppress this background before acceleration has been performed[1] at the Rehovot 14-UD Pelletron tandem accelerator. The basic idea is to deplete negative ions of stable isobars by selective electron detachment with a laser beam, leaving the radioisotope ions unaffected. The method is relatively straightforward for cases where the electron affinity (EA) of the radioisotope is larger than the one of the interfering isobar. Such a case of practical importance is ^{36}Cl (EA = 3.62 eV), where the EA of the interfering ^{36}S is 2.08 eV. An effective removal of ^{36}S before acceleration would be a very desirable feature for ^{36}Cl measurements, in particular at the smaller tandem facilities where ^{36}Cl cannot be measured at natural levels at the present time.

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†Weizmann Institute of Science, Rehovot, Israel.
[1]D. Berkovits et al., to be published in Nucl. Instrum. Methods A (1989).

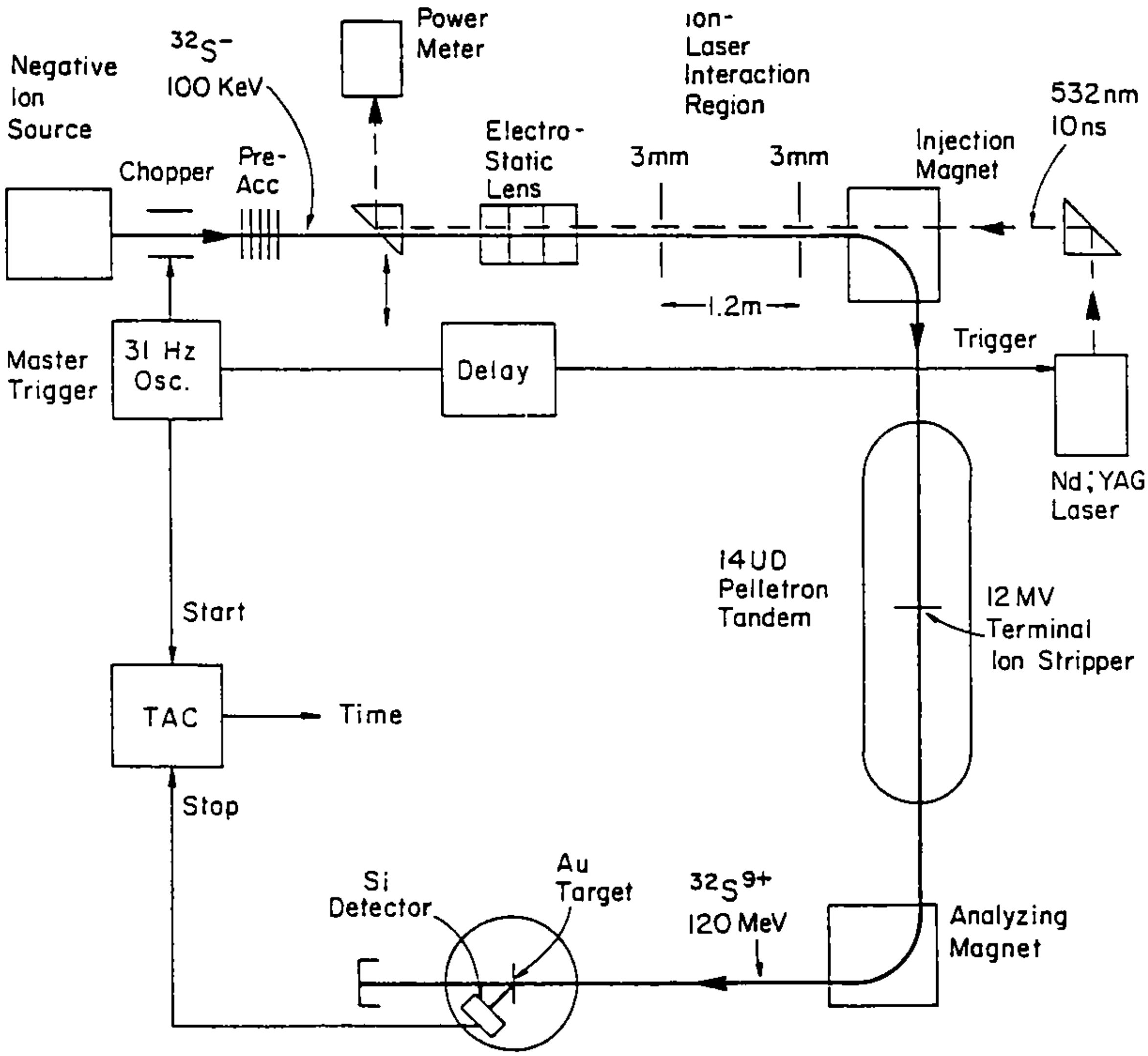

Fig. I-13. Schematic presentation of the experimental setup to study laser suppression of negative ions.

Figure I-13 shows a schematic layout of the experimental setup, where the interaction of 532-nm photons (=2.33 eV) from a Nd:YAG laser with negative ions was studied. Both ion beam and laser beam were operated in a pulsed mode with pulse lengths of 13 μs and 10 ns, respectively. With a proper time delay between the pulses, the interaction was confined to a region between two 3-mm apertures. A series of time spectra measured with this arrangement is shown in Fig. I-14. With an effective laser photon density of 4.3×10^{17} photons/cm^2 in the interaction region, a strong depletion of a $^{32}S^-$ beam was observed. A $^{37}Cl^-$ beam subjected to a similar photon density did not show any measurable depletion. In order to get information on a possible suppression of isobaric ^{41}K in AMS measurements of ^{41}Ca, we investigated the case of a $^{40}CaO^-$ beam and observed a strong depletion by laser interaction, indicating that the EA of this molecule is lower than 2.33 eV. From a measurement of the negative ion depletion as a function of laser power, electron detachment cross sections of $(1.0\pm0.2) \times 10^{-17}$ and $(7\pm3) \times 10^{-17}$ cm^2 were measured for $^{32}S^-$ and $^{40}CaO^-$.

The present results demonstrate that, in principle, a selective depletion of ^{36}S in AMS measurements of ^{36}Cl is feasible. For a ^{41}K suppression in ^{41}Ca measurements, it will depend on whether KO^- has the lower EA than CaO^-. To our knowledge, the EA of none of these ions has yet been measured. For actual AMS measurements, which require a high overall detection efficiency, a number of improvements over the current system have to be implemented (e.g. pulsed ion source operation).

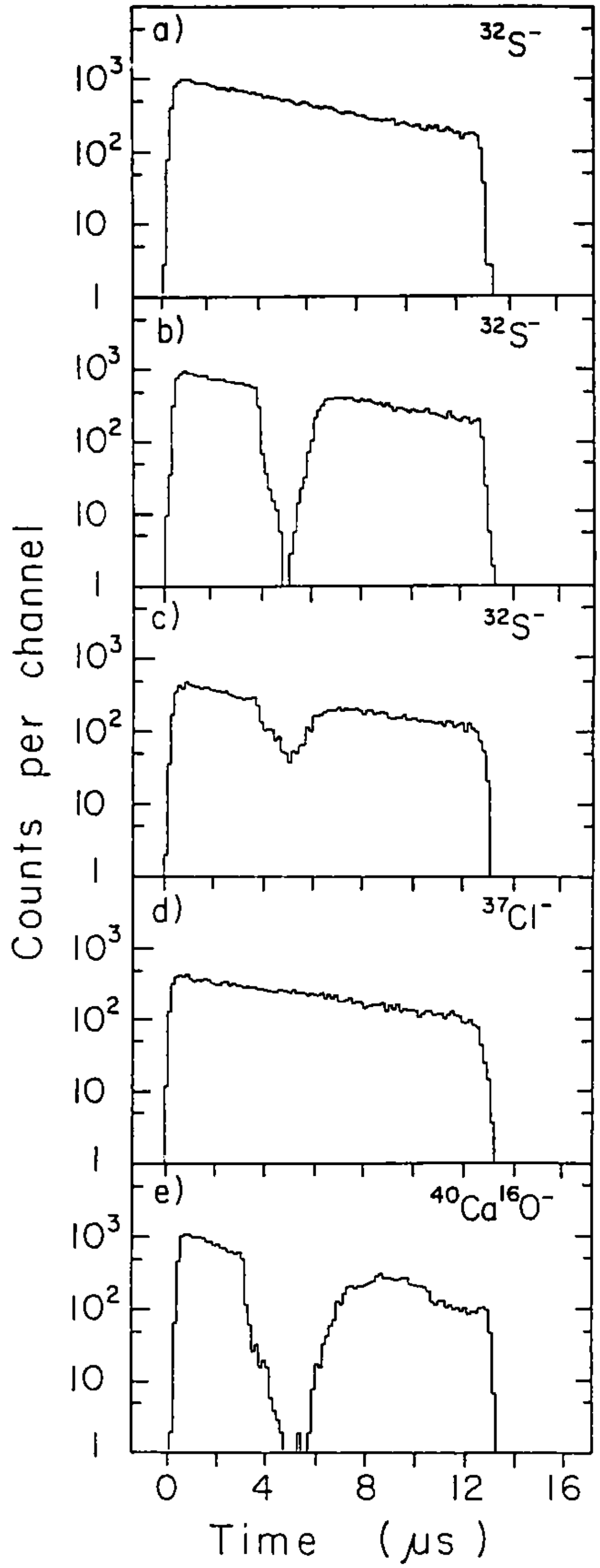

Fig. I-14. Time spectra measured for different negative-ion beams and different laser pulse densities in the interaction region. a) laser off; b) laser on, ϕ = 4.3 x 10^{17} photons/cm^2; c) laser on ϕ = 7.6 x 10^{16} photons/cm2; d) laser on, ϕ = 5.5 x 10^{17} photons/cm^2; e) laser on, ϕ = 5.1 x 10^{17}.

E. OTHER TOPICS

In addition to the above programs, there are a number of other research efforts in heavy-ion research. Extensive calculations have been performed on several aspects of crystalline structure in cooled, confined ions in traps or storage rings. In anticipation of U beams in 1991, preparation has begun for measurements to ascertain the nature of the correlated positron-electron sharp lines observed in heavy-ion scattering experiments at GSI. Nuclear astrophysics experiments have been undertaken to measure the γ width of the $^{14}O^*$ (5.17-MeV) state of relevance for the hot-CNO cycle, and the lifetime of the 2.3-keV state in ^{205}Pb, of relevance to the possible use of ^{205}Tl as a solar-neutrino detector.

a. Positron Experiments at ATLAS

Within the next two years the ATLAS facility will have the capability of accelerating all ions up to and including uranium. This offers the possibility of experiments designed to study the physics of extremely high-Z quasi-atoms which can be formed in the collisions of these very heavy ions. Experiments of this type have hitherto only been possible at the GSI, Darmstadt UNILAC and the LBL, Berkeley SuperHILAC. The upgraded ATLAS facility offers a vastly improved duty cycle over these facilities and it is expected that the ECR source and injector will provide beam intensities far in excess of those currently available for the heaviest ions. Experiments to date at GSI have revealed one of the most puzzling phenomena in physics today - the narrow lines observed in the spectra of positrons emitted in collisions of U + U and similar systems. This result is not even qualitatively understood at the present time and explanations varying from the formation of a giant nuclear molecule to the decay of an "elementary" neutral object have been proposed.

We plan to carry out an experiment to try to further elucidate the nature of these narrow peaks and have submitted a proposal for a new apparatus to do so. Briefly, the proposed apparatus consists of a large (4-m long, 1-m diameter) solenoid mounted transverse to the beam direction. Electrons and positrons produced at the target position in the center of the solenoid, spiral down the solenoid and are detected in a highly-segmented, pencil-like silicon array placed close to the end of the solenoid. Positrons are identified by a coincidence requirement with two annihilation photons detected in a cylindrical scintillation array. The angles of emission of electrons and positrons are determined using time-of-flight and the segmentation of the silicon array.

This device, in addition to superior count-rate capabilities as compared to the existing GSI experiments, will allow the measurement of the invariant mass of the decaying object, if indeed this is the correct explanation of the positron peaks. The most provocative of the current hypothetical explanations will thus be tested directly.

The planned ATLAS Positron Experiment "APEX" will be carried out as a collaborative effort between scientists from Argonne, Florida State, Michigan State, Princeton and Yale. Following an informational meeting held at last year's Baltimore APS meeting, the collaboration was formed and has met some five times since. After deciding on the overall aims of APEX, the collaboration developed and evaluated a number of design options. These were: the large solenoid eventually selected as the proposed device, a double-orange spectrometer, a mini-orange ball, a time-projection chamber and solenoids with various other detector configurations. A proposal has been submitted requesting equipment funds for a large solenoid which is expected to be ready for operation in early 1991.

The current members of the APEX collaboration are:

Argonne: I. Ahmad, R. Betts, R. Dunford, S. Freedman, J. Last, E. Rehm, J. Schiffer, F. Wolfs

Florida State: J. Fox

Michigan State: S. Austin, E. Kashy, M. Maier, D. Mikolas, J. Winfield

Princeton: F. Calaprice, A. Hallin

Yale: J. Greenberg.

a.1. Solenoid Design Studies (F. L. H. Wolfs and R. R. Betts)

A number of designs for an electron positron spectrometer utilizing a solenoidal magnetic field have been studied. The design selected for the APEX proposal consists of a large (4-m long, 1-m diameter) solenoid with a uniform 300-Gauss field, mounted transverse to the field direction. Electrons and positrons emitted from the target in the center of the device are detected in two 36-cm long, 3-cm diameter segmented silicon detector arrays placed with their far ends 156 cm from the target position. Each array will be a hexagonal cylinder of side length 1.5 cm with faces covered with 36 detector elements 3-cm long and 0.5-cm across. The detectors will be fabricated as 1-mm thick PIN diodes in modules of six detector elements on a single piece of silicon. The detector arrays will be cooled. Energy and time information will be obtained using time pickoff units mounted close to the ends of the array so as to minimize the capacitance seen by the input of these units.

The angles of emission of electrons and positrons will be determined using their measured energies, impact positions and time of flight, with an expected energy and time resolution of 5 keV and 1.5 ns, respectively. The device will give an angular resolution $\Delta\theta = 10^{\circ}$ and $\Delta\phi = 20^{\circ}$ FWHM for 400-keV electrons and positrons. The positron identification is accomplished by a time coincidence between a silicon detector event and the detection of two 511-keV annihilation photons in a barrel-shaped array of BaF_2 crystals which surrounds each of the silicon arrays. These scintillation arrays are shielded from direct radiation from the target by conical plugs of light-element-coated heavy metal which also serve to suppress the intense flux of low-energy electrons by acting as baffles to stop the small-pitch spiral trajectories. The total detection efficiency of this device for electrons and positrons between 200 and 650 keV, including all effects such as backscattering and detection efficiency of the annihilation radiation, is 9.0% of 4π. The coincidence efficiency for electron-positron pairs is 5.6% of 4π. Including the improvement due to the duty factor of ATLAS compared to the GSI UNILAC, the proposed experiment represents at least a factor-of-20 improvement in count-rate capabilities over the first-generation experiments and in addition features angle measurement of the detected particles.

A number of simulations of various background processes have been made using measured spectra of electrons and photons as input to the Monte Carlo code EGS. It has been concluded from these studies that the major source of background, scattered photons, is reduced to an extremely small level by the stringency of the two-annihilation photon-trigger requirement. It may prove possible to relax this requirement to one of a single 511-keV photon for the trigger. In that case the detection efficiency is improved by a factor of two.

a.2. Design Study for a Double-Orange Spectrometer (K. E. Rehm and R. W. Dunford)

For the planned positron-electron coincidence experiment with U-beams from the new positive-ion injector, the possibility of using orange-type spectrometers was investigated. If compared to the existing double-orange spectrometer at GSI, the new device should have improved efficiency, a clear signature for positron detection, and a better θ and ϕ-resolution. Various spectrometer designs with and without a focal plane were investigated. The final spectrometer design consists of two independent iron-free orange spectrometers positioned in similar geometry to those at GSI. The entrance- and exit-field boundaries were chosen to obtain a large energy acceptance, to minimize effects of the fringe field on the trajectories and to obtain a good angle determination from a measurement of energy and position in the detector array. Trajectories for positrons with energies of 300, 400, and 500 keV emitted at various angles are shown in Fig. I-15. There is a unique single-valued correlation beteween energy position and emission angle, so that if two quantities are measured, the third can be determined. The price for obtaining good angle resolution $\Delta\theta$ (about 3^{o} for a position resolution of 2 cm) is the lack of a real focal plane. This type of spectrometer, which has not been built before, therefore does not have the redundant energy information from the position measurement in the focal plane which is used effectively for background reduction in the GSI experiment. In order to obtain a clear signature for a positron being detected in the Si-array, the use of a cylindrical BGO detector for annihilation detection is proposed on the positron side of the double-orange spectrometer. The use of a multi-wire proportional counter with 60 wires would improve the ϕ-resolution to $\pm 3^{o}$. In all cases the angle resolution would not be limited by the detection device, but by the small-angle scattering in the target, which is estimated to be around 8^{o} for a

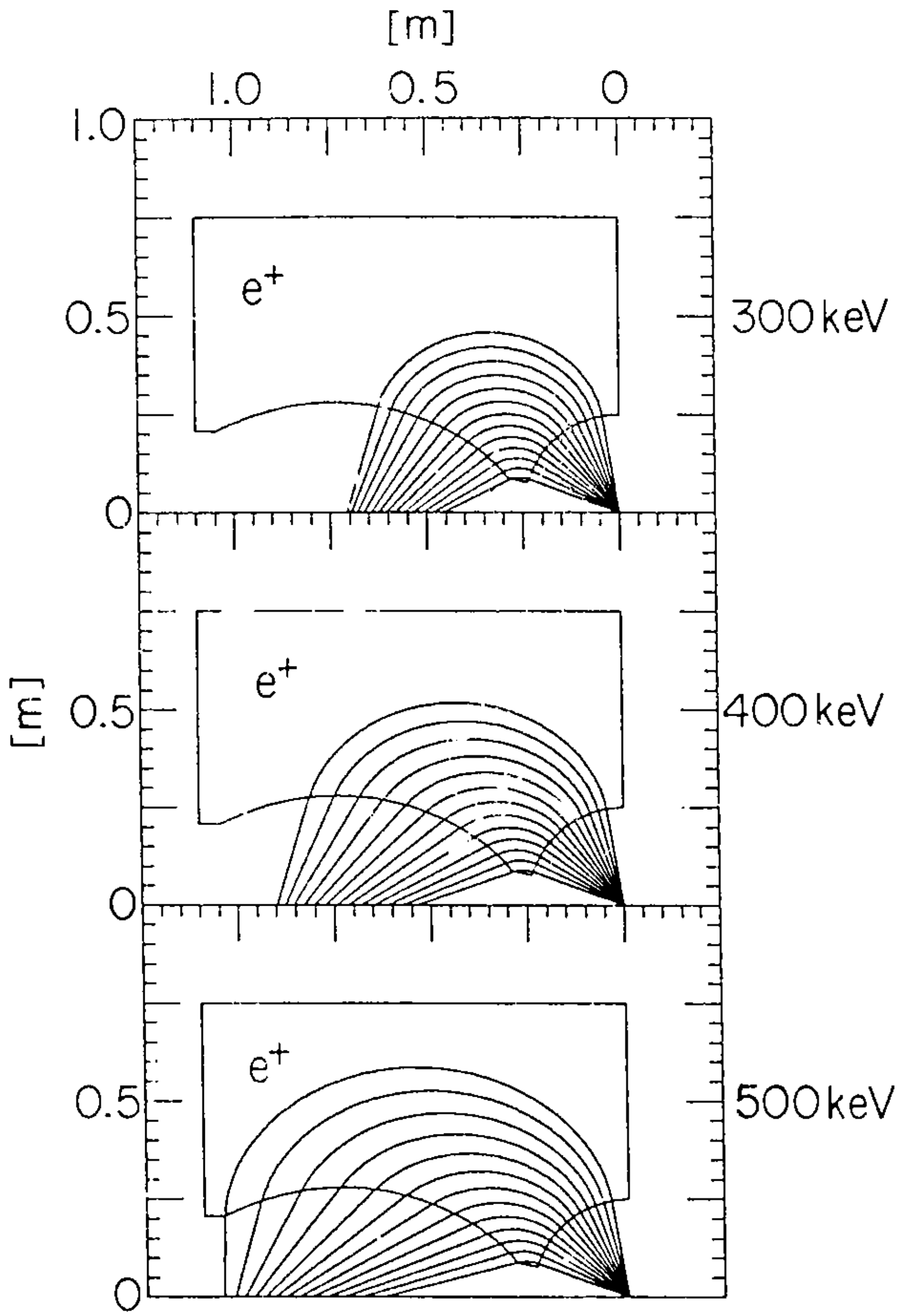

Fig. I-15. Trajectories for positrons emitted in the angular range between 100°-160° and energies of 300, 400, and 500 keV.

300 $\mu g/cm^2$ U-target. The total efficiency of the double-orange spectrometer is calculated to be 10.2% for singles and 5.8% for electron-positron coincidences over the energy range between 300 and 550 keV. Extensive trajectory calculations for background electrons and positrons produced at various places in the spectrometer have been performed. It turned out that the main sources for background are scattered γ-rays which produce energy signals up to about 200 keV in the Si-detectors and δ-electrons scattered off the Cu-coils. The use of a MWPC should reduce the γ-background and also help to distinguish the scattered electrons by a coarse track reconstruction using the ϕ-information from the MWPC and the Si array. This new spectrometer design might also be useful in other fields where the scattering angles θ and ϕ of charged particles have to be measured with good efficiency.

a.3. Monte Carlo Studies (J. Last and R. R. Betts)

In order to assess the design criteria for the APEX experiment, a series of simulations have been carried out designed to investigate the effect of various experimental resolutions on the extraction of physical quantities from the data. Specifically, we have investigated the importance of the angular resolution in the determination of the invariant mass of a neutral object decaying to electron-positron pairs. The process simulated was that of the decay of an object of mass 1.8 MeV formed at rest in the center of mass of the ion-ion system. This object was assumed to decay isotropically in this frame to a positron-electron pair which, after multiple scattering in the target material, are detected in various experimental geometries with differing acceptances and resolutions. It was found that in most cases, the target thickness is the factor hurting the resolution in the derived invariant mass, which can in realistic cases be determined with a resolution of approximately 40-keV FWHM.

a.4. Detector Testing

Vital components in the proposed APEX experiment are the silicon detector arrays which must detect electrons and positrons of energies of a few hundred keV with excellent energy and time resolution. It is proposed that these arrays consist of PIN diodes which are available cheaply in the chosen geometry - a number of simple prototypes have been tested and evaluated. In addition to the silicon arrays, the APEX experiment requires the identification of annihilation photons in coincidence with positron hits on the silicon array. The phototubes on this scintillation array must operate in a magnetic field and tests have been made to show that this is indeed possible.

a.5. Response of a Hamamatsu 0.5-mm PIN Diode to Electrons (I. Ahmad, R. R. Betts, and D. J. Henderson)

The device proposed for the measurement of sharp positron lines produced in $^{238}U + ^{238}U$ collisions requires silicon detectors with excellent energy and time resolution. For this reason, we have tested 0.5-mm thick Hamamatsu PIN diode detectors. These detectors are operated at a bias of 100 volts and at this bias they have leakage currents of 2-5 nanoamperes. The purpose of the test was to obtain high resolution on the energy as well as time signals. We used an Ortec H242B preamplifier which has a time pickoff for timing and a conventional charge-sensitive loop for the energy signal. We measured an energy resolution (FWHM) of 3.8 ± 0.2 keV for the ^{139}Ce 165.9 keV line at room temperature. The timing spectrum was obtained by starting a TAC with 300-500-keV electrons detected in the Si detector and stopping the TAC with the 605-keV peak of ^{134}Cs in a 2.5 in. x 2.5 in. barium fluoride crystal. A resolution (FWHM) of 1.5 ± 0.1 ns was measured. The addition of 1 ft and 2 ft of cable gave resolutions of 1.9 ns and 2.1 ns, respectively. These measurements show that there is only slight increase in time resolution with an increase in capacitance. The energy resolution changed from 5.0 keV to 7.0 keV when 2 ft of cable was added between the detector and the preamplifier. These detectors can only detect electrons and positrons up to 450 keV and are thus too thin to be used in the positron device. However, the present tests indicate that the performance of a silicon detector does not deteriorate significantly with the addition of up to 2 ft of cable (60-pf capacitance).

a.6. Timing Characteristics of Cooled PIN Diodes (J. Ahmad, R. R. Betts, and D. J. Henderson)

The aim of the proposed device is to measure electrons and positrons in the energy range of 200-700 keV. Thus the minimum thickness needed for the silicon detector is 1 mm. We have obtained several 1-mm thick silicon detectors from MICRON Ltd. These detectors have high leakage currents (200-400 nA) at room temperature and hence cannot be effectively used at room temperature. We have tested these detectors using an Ortec H242B preamplifier and ^{139}Ce and ^{134}Cs sources. Measurements were made by cooling the detector with a coolant at -20^{o}C and also by liquid nitrogen. The temperature of the detector was not directly measured. At -20^{o}C we measured an energy resolution of 7.0 keV and timing resolution of 2.2 ns for 300-500 keV electrons. By cooling with liquid nitrogen, energy and time resolutions of 4.5 ± 0.2 keV and 1.2 ± 0.1 ns were achieved. These numbers are adequate for the positron device. Addition of cables between the detector and the preamplifier will worsen the performance of these detectors only slightly as demonstrated by the tests at room temperature. These effects are currently being investigated further.

a.7. Tests of Phototubes in Magnetic Fields (J. Last and R. R. Betts)

The scintillation array for the APEX experiment must operate in a magnetic field of 300 gauss. It is not possible to shield the phototubes without disturbing the uniform field required for the experiment. We have tested a tube (Hamamatsu R2490) designed for operation in fields of up to 10 kG. This tube has a 16-stage mesh-type dynode structure, closely spaced so the electron trajectories are not perturbed by external fields. Our measurements show a decrease in gain of only 10% going from zero field to 1 kG. This performance is adequate for the experiment.

b. Indirect Determination of the $^{13}N(p,\gamma)^{14}O$ Reaction Rate in the Hot-CNO Cycle (T. F. Wang, K. E. Rehm, S. J. Sanders, C. N. Davids, B. G. Glagola, R. Holzmann, W. C. Ma, P. V. Magnus,* P. D. Parker,* and M. Smith*)

In high-temperature and high-density astrophysical environments (such as accreting neutron stars, novae, and white dwarfs) the normal CNO cycle may be transformed into the Hot-CNO cycle:

$$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^{+}\nu)^{14}N(p,\gamma)^{15}O(\beta^{+}\nu)^{15}N(p,\alpha)^{12}C \ .$$

The $^{13}N(p,\gamma)^{14}O$ reaction which bypasses the normal ^{13}N beta decay is the key reaction in the Hot-CNO cycle. A determination of the $^{13}N(p,\gamma)^{14}O$ reaction rate is essential in order to determine at what temperatures and densities proton capture on ^{13}N will become faster than its beta decay.

Because of the short half-life of ^{13}N(~ 10 min.), it is not yet possible to make ^{13}N either as a beam or as a target in order to make a direct measurement of this reaction rate. However, at the temperatures of interest, $T < 10^9$ K, the rate of this reaction is determined by the properties (the resonant energy, the total width, and the gamma-ray width) of the low-energy ($E_{c.m.}$ = 541 keV) s-wave resonance corresponding to the first excited state of ^{14}O. The total width and the resonant energy of this state have been measured (Γ = 38.1 ± 1.8 keV, E_x = 5168.5 ± 1.8 keV); the remaining unknown gamma-ray width can be determined by measuring the gamma-ray branching ratio (Γ_γ/Γ) of this state.

By choosing the $^1H(^{14}N,^{14}O)n\gamma$ reaction and a 175-MeV ^{14}N beam from the ATLAS accelerator, the recoil ^{14}O nuclei from the gamma-ray decay of the $^{14}O^*$(5.17 MeV) state will all be confined within a ± 1° cone centered at 0°. The major technical difficulty of this measurement is separating the beam (and beam-related products) from the recoil ^{14}O nuclei. Using an Enge split-pole spectrograph and its associate "Bragg-curve" detector system we have successfully identified the $^{14}O_1$ recoils corresponding to events in which an $^{14}O^*$(5.17-MeV) was initially formed and then decayed by gamma-ray emission.

*Yale University, New Haven, CT.

This measurement must be combined with the measurement of the ratio of the production cross sections for these recoils in order to determine the Γ_γ/Γ of the 5.17-MeV state. Our preliminary results can be expressed in terms of the production cross-section ratio as $\Gamma_\gamma/\Gamma = (3.6 \pm 1.7) \times (\sigma_{n0}/\sigma_{n1}) \times 10^{-5}$ or as $\omega\gamma = (1 \pm 0.5) \times (\sigma_{n0}/\sigma_{n1})$ eV. We also carry out a preliminary $^{14}O^*$-γ coincidence experiment while we are collecting the $^{14}O^*$ singles. The preliminary results from this coincidence measurement [$\omega\gamma \sim (0.75 \pm 0.25) \times (\sigma_{n0}/\sigma_{n1})$ eV] is consistent with the result of our singles measurement. Further work on either determining the σ_{n0}/σ_{n1} ratio via the $^{14}N(p,n)^{14}O$ reaction or carrying out the n_1-$^{14}O_1$ coincidence measurement is currently in progress.

c. Lifetime of the 2.3-keV State in ^{205}Pb (T. F. Wang, I. Ahmad, D. Henderson, and C. N. Davids)

Neutrino capture in $^{205}T\ell$ to populate levels in ^{205}Pb provides a sensitive solar-neutrino detector for two reasons. First, the low threshold (~ 43 keV) in the $^{205}T\ell(\nu,e^-)^{205}Pb$ reaction makes it sensitive to most of the solar p-p neutrinos and second, the long half-life (~ 15 million years) of ^{205}Pb makes it insensitive to fluctuations in solar-neutrino flux. However, to use this reaction as a solar-neutrino detector one needs the neutrino capture cross sections to levels in ^{205}Pb. The largest cross section is expected for the capture to the 2.3-keV state. One way to determine this cross section is to measure the probability for the inverse reaction, namely electron capture decay branch from the 2.3-keV state in ^{205}Pb. To determine this, one needs the lifetime of the 2.3-keV level, which gives the total decay width.

In our first attempt of determining the lifetime of this 2.3-keV state, a thin ^{209}Po source on a thin film was used. Alpha decays from ^{209}Po populate predominantly the ground state and the 2.3-keV state in ^{205}Pb, and the decay of the 2.3 keV state will produce conversion electrons. An alpha-electron delayed-coincidence measurement using a Si detector (to detect the alpha particles) and an ionization chamber (to detect the conversion electrons) was carried out. The TAC spectrum shows two peaks; the second peak has been identified as events from alpha-^{205}Pb recoil (energy ~ 100 keV) coincidences.

We have improved the experiment by using a small magnet and a channel-plate detector to detect the conversion electrons; the recoil ^{205}Pb nucleus has different rigidity which removes it from causing complications in the TAC spectrum. Our preliminary result shows that the lifetime of the 2.3-keV state is 150 ± 40 ns. Further improvement on the efficiency and the energy resolution of the magnetic device and its channel-plate detector system is in progress. Our future work will involve improvements of the error in the lifetime measurement as well as determining the alpha-decay branches of ^{209}Po to the ground and the first excited state in ^{205}Pb.

d. Possible Condensed Crystalline State in Confined Ions
(J. P. Schiffer)

A program to better understand the properties of confined cold ions, such as may be obtained in ion beams and in ion traps, is being continued. Calculations are carried out using the Energy Research Cray and a Molecular Dynamics program initiated by the late A. Rahman. Work in the past year has been done to further explore the limitations in real storage rings from shear, periodic focusing, and the limitations of cooling mechanisms. In the past year the crystalline layered structures predicted by our calculations have been observed by the National Bureau of Standards group at Boulder, largely confirming the predictions (see Fig. I-16). Calculations are being conducted to better understand these results as well as those expected in ion beams. An experiment is planned at the IUCF storage ring to begin the exploration of collective properties of cold ion beams.

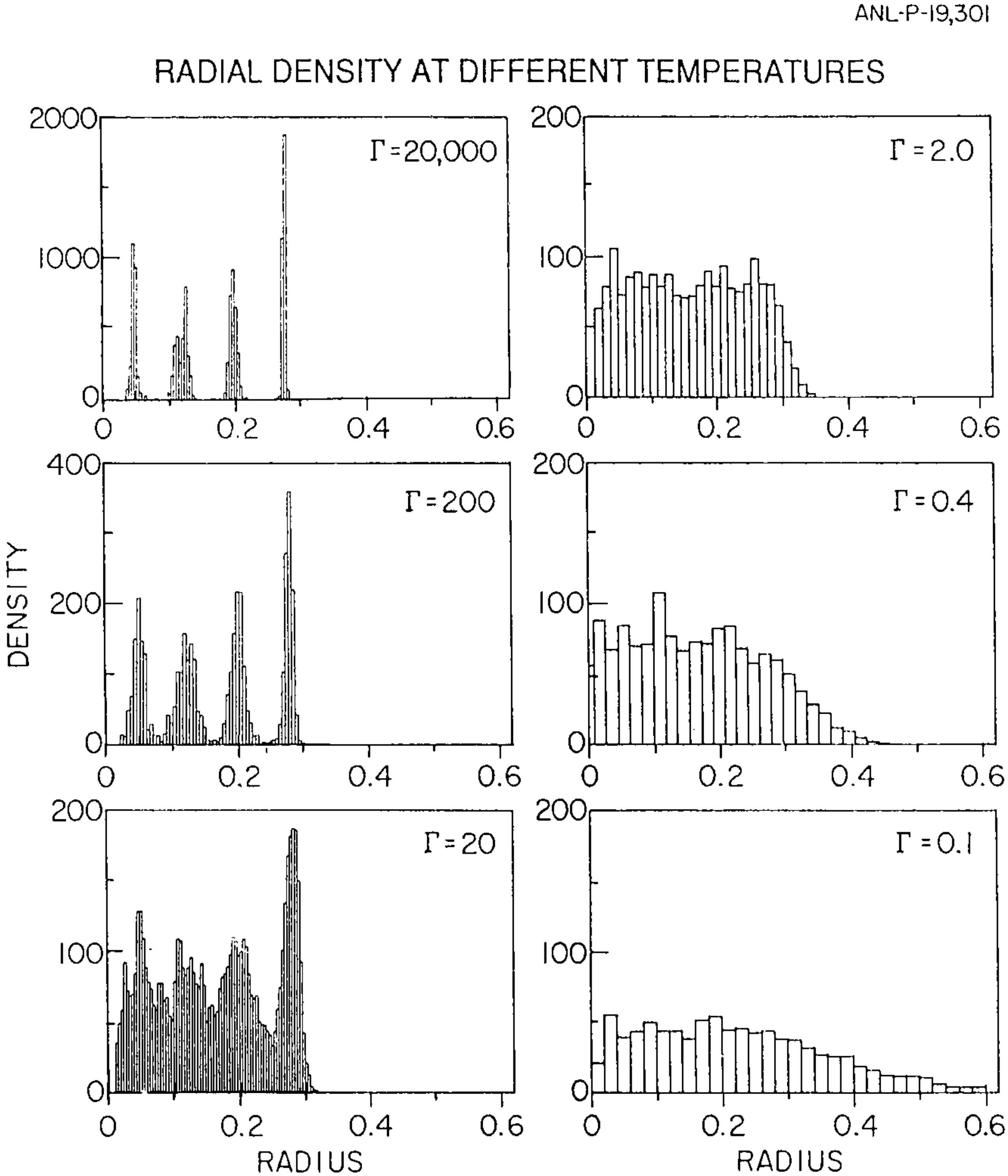

Fig. I-16. Radial density distributions of an ion beam from model calculations with cylindrical confinement as a function of temperature. Γ is a dimensionless quantity that is proportional to the reciprocal of the temperature.

d.1. Normal Modes in Ion Beams (J. P. Schiffer)

In our earlier work it was shown that under the cylindrically-symmetric confinement that characterizes the time average of the focusing forces acting on an ion beam, a cooled beam will settle to a configuration with minimum energy; the particles condense into concentric shells and form a hexagonal pattern within each shell. The radial normal modes of such a system were studied, and two were identified: a monopole breathing mode, and a quadrupole mode, with frequencies corresponding to the betatron frequency and 1.4 times that (see Fig. I-17). It has now been shown that above a threshold density these frequencies are essentially independent of the number of particles. These modes are quite robust: they seem to persist, with frequencies unchanged, up to temperatures several orders of magnitude above the region where the layered structures dissolve into a more uniform distribution.

[1] J. P. Schiffer and A. Rahman, Z. Phys. 331, 71 (1988).
[2] John P. Schiffer, Workshop on Crystalline Ion Beams, Wertheim/Main, Germany, Oct. 4-7, 1988 (to be published).

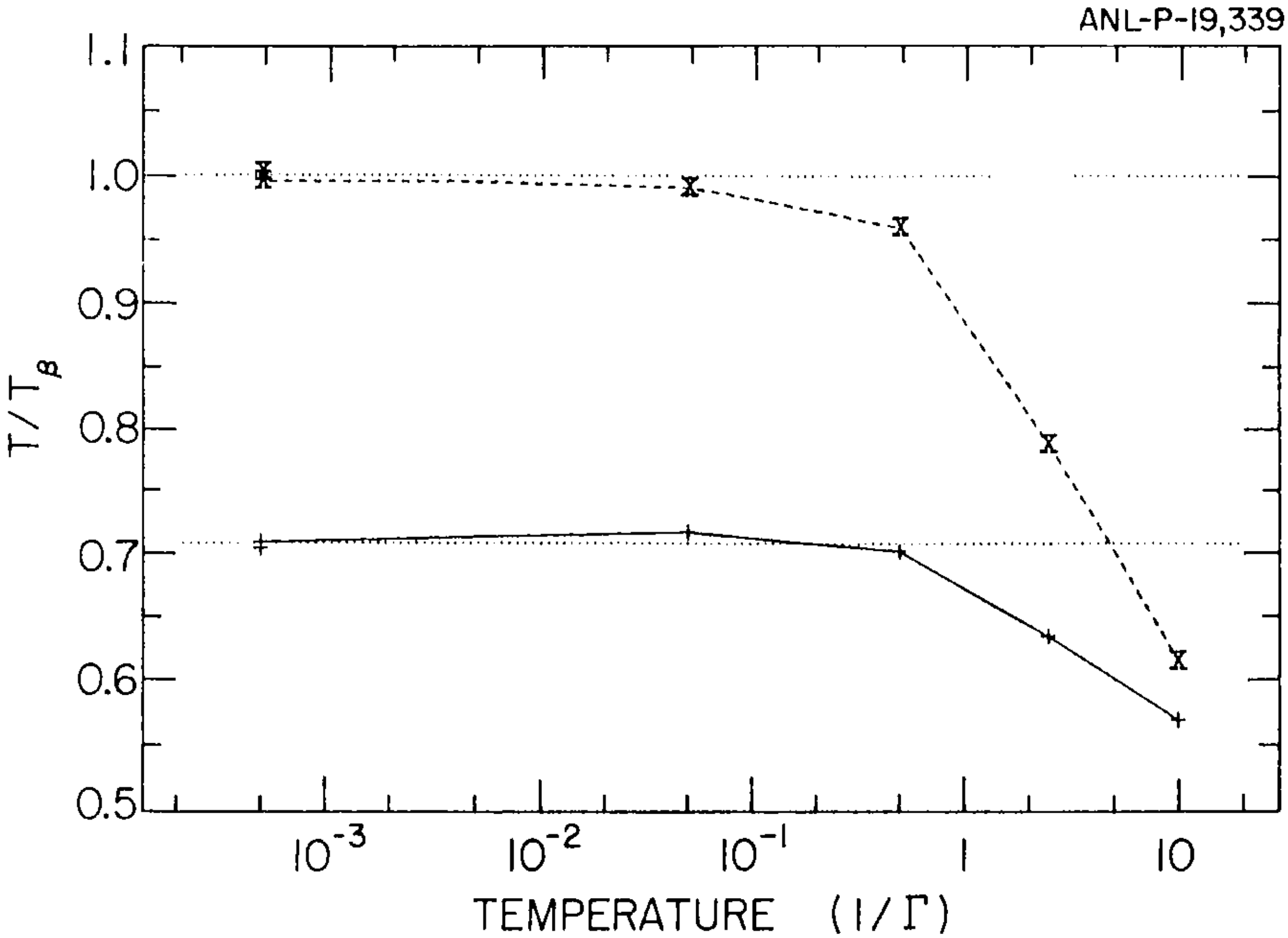

Fig. I-17. Frequencies of two radial modes associated with cold particle beams as a function of temperature in units of 1/Γ.

d.2. Shear in a Particle Beam Stored in a Ring (J. P. Schiffer)

The standard electron cooling mechanisms used in storage rings cause particles to travel with the same velocity. In a condensed state this means that the circular motion around a storage ring inevitably introduces a shear into the system. Calculations seem to indicate that for the storage rings under construction now, such shear is beyond the elastic limits of a condensed system and would therefore disrupt the ordered state (see Fig. I-18). Several avenues have been explored. One solution would be a storage ring with much stronger focusing (higher betatron tune) than those in current cooler rings, approaching the values in RHIC or the SSC. Another possibility that is not necessarily out of the question, is to introduce a small radial velocity gradient into the beam, either through the cooling mechanism or by other means, and thus allow the particles to travel around the ring, locked together. Some model calculations have also been tried, allowing the particles to slip with respect to each other under the shear, while imposing continuous cooling -- in this case the particles in the model settle into long ordered strings, which slide with respect to each other.

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[1] J. P. Schiffer and A. Rahman, Z. Phys. 331, 71 (1988).

[2] John P. Schiffer, Workshop on Crystalline Ion Beams, Wertheim/Main, Germany, Oct. 4-7, 1988 (to be published).

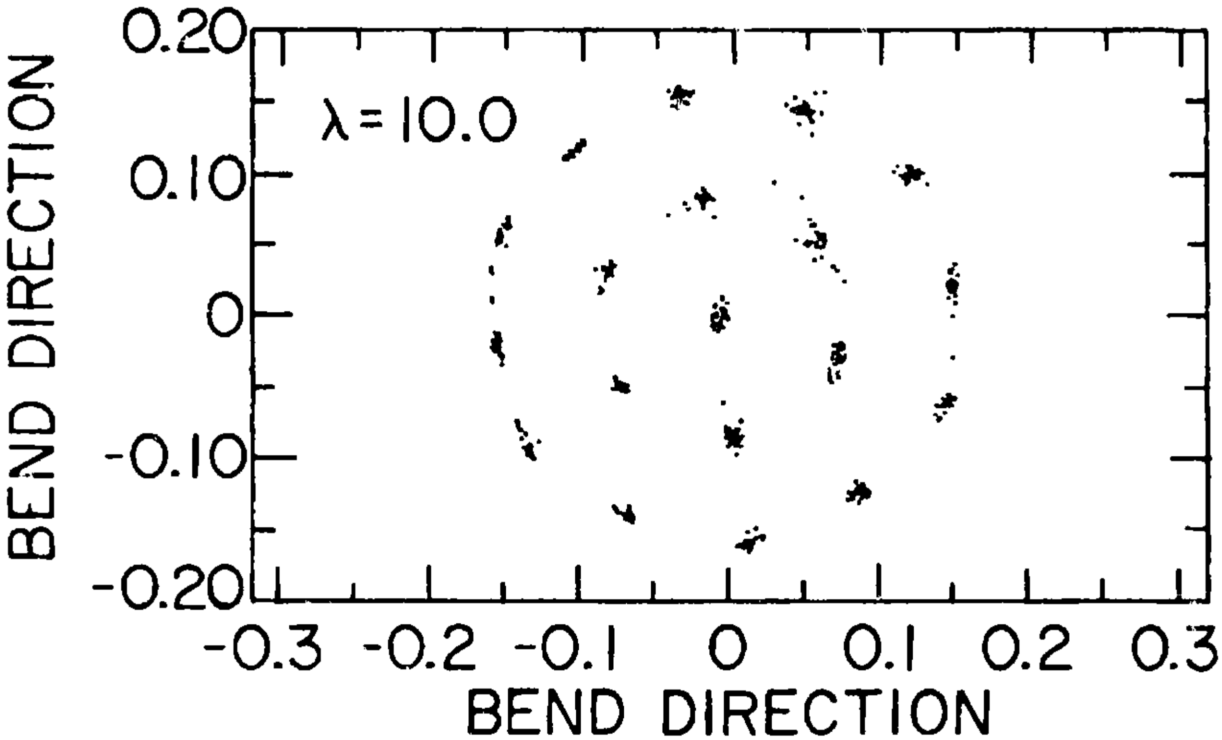

Fig. I-18. Projection of particles onto a plane perpendicular to the beam for a model system that was subjected to continuous cooling and shearing.

d.3. Periodic Focusing and Cooling in Storage Rings (J. P. Schiffer)

The initial calculations for cold ion beams assumed a constant focusing force and steady cooling. In real storage rings the focusing is periodic, largely from the magnetic focusing lenses along the ring, and the cooling is applied once per turn and only along the beam direction. The question to be answered is whether the ordered state calculated under ideal focusing and cooling conditions could still be achieved with a more realistic cooling mechanism and focusing lattice. Model calculations have been carried out introducing periodic focusing at about the rate at which this would occur in a storage ring, and cooling corresponding to the once-a-turn rate and only along the beam direction. It was found that even under these circumstances a random beam did settle eventually (a time corresponding to several tens of turns in a ring) into the ordered shell structure noted under more ideal circumstances. No shear was introduced into these calculations.

[1]John P. Schiffer, Workshop on Crystalline Ion Beams, Wertheim/Main, Germany, Oct. 4-7, 1988 (to be published).

d.4. Study of Quasi One-Dimensional Systems (J. Hangst* and J. P. Schiffer)

At low densities cold particles in an ion beam settle on the mean beam axis and the degree of ordering is a gradual one. Order in one-dimensional Coulomb systems had been studied some time ago by Dyson, who pointed out the relation between this order and the distribution of level spacings in compound nuclei. Various measures of order are being explored by modelling calculations, that may have some applications to new diagnostic techniques that have been proposed.

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

d.5. Proposed Experiment at the IUCF Storage Ring (J. Hangst*, J. P. Schiffer, R. E. Pollock†, T. Ellison† and D. Friesel†)

The normal modes referred to in d.1. above may be detectable even for lightly-charged beams, such as the cooled proton beams at the Indiana University Cyclotron Facility. A proposal has been submitted in 1988 and has received approval for beam time. The experiment will make use of the existing diagnostic system at the cooler ring, the Schottky probes in particular, to investigate these modes that should occur at well-defined frequencies.

*Graduate Student, University of Chicago, Chicago, IL.
†Indiana University Cyclotron Facility, Bloomington, IN.

d.6. Three-Dimensionally Confined Ions (J. P. Schiffer)

The observations in the Spring of 1988 by the Boulder National Bureau of Standards group of layered structures in a Penning trap confirmed our prediction of such structures under three-dimensional confinement. Even quantitative predictions, relating the number of shells to the number of particles, were confirmed. Since the confinement in their Penning trap was anisotropic, model calculations were carried out to simulate this, and the spherical structures became spheroidal. The Boulder results indicate that the structures are sometimes spheroidal but at other times they appear to be cylindrical. When heavy impurities are introduced into the calculations (similar to what is thought to be present in the Boulder system under some circumstances) the shapes of the calculated structures do change into more nearly cylindrical ones. The role of shear, between different sections of a spheroidal cloud may also play a role in this and has been partially investigated in the modelling calculations.

[1]John P. Schiffer, Phys. Rev. Lett. 61, 1843 (1988).

d.7. Normal Modes of Three-Dimensionally Confined Ionic Systems (J. P. Schiffer)

A set of calculations have been started in order to investigate the normal collective oscillatory modes of a spherical or spheroidal cloud of ions. Clear monopole radial oscillations and quadrupole shape oscillations are found. The dependence of these modes on the spheroidal deformation of the cloud remains to be investigated.

d.8. Structure of Small Three-Dimensionally Confined Ionic Systems (R. Rafac and J. P. Schiffer)

A cloud of a few (<25) charged particles, confined in an isotropic potential settles into a well-defined geometric pattern. The symmetry of such systems has been of interest for at least 100 years, since J. J. Thomson's model of the atom, however contradictory statements appear in the literature about the lowest energy configurations. The Molecular-Dynamics technique has been applied to find these minimum solutions, and the lowest energy configuration identified, and compared with those in the literature. Up to 12 particles arrange themselves on a spherical, or approximately spherical, surface and only with 13 particles does one sit at the origin (see Fig. I-19). The simple degrees of freedom for these systems are being investigated.

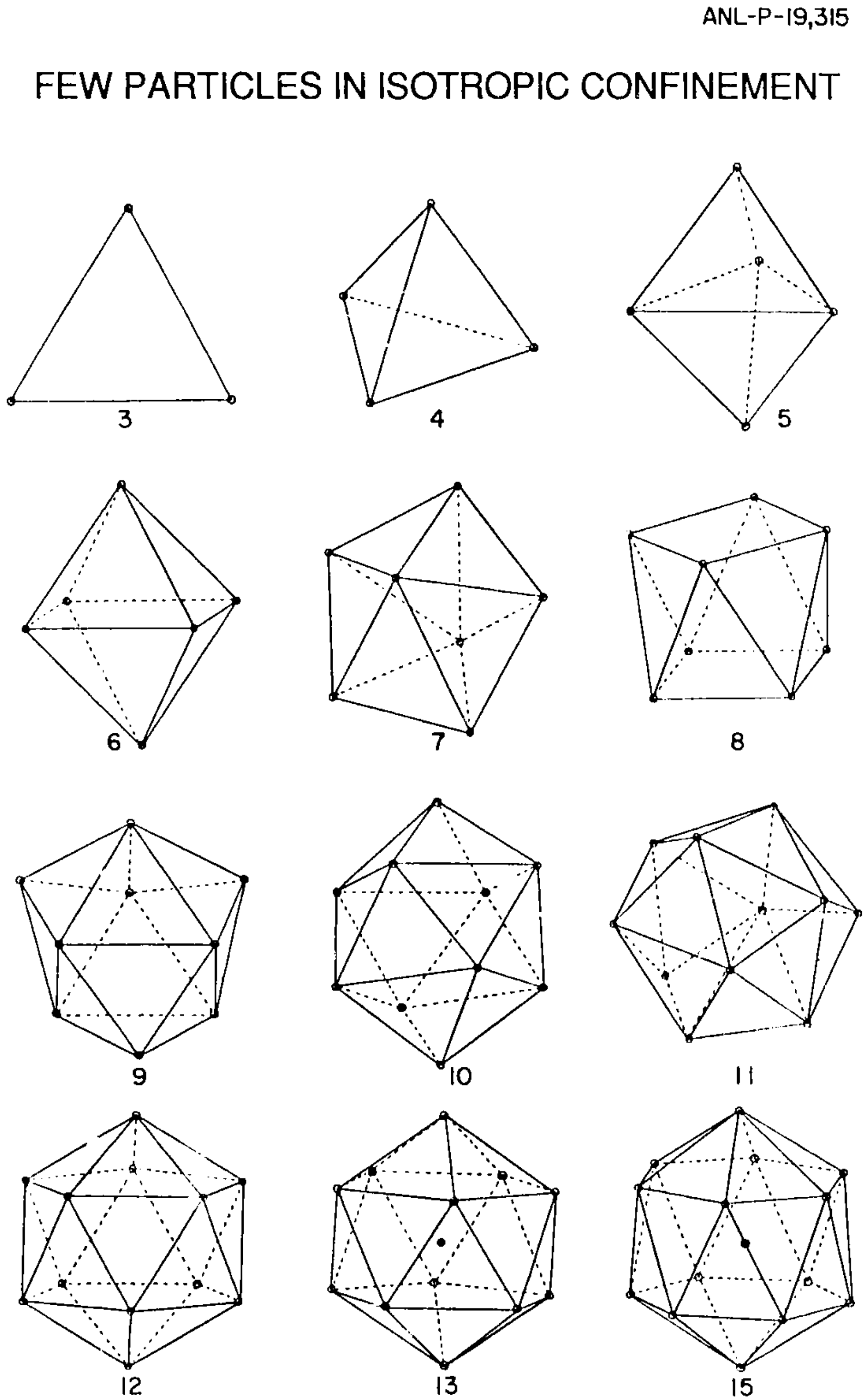

Fig. I-19. Configuration of few particles in a spherically symmetric confining potential.

F. EQUIPMENT DEVELOPMENT AT THE ATLAS FACILITY

Major effort during the past year was focused on the two experimental stations (i.e.,the Fragment Mass Analyzer (FMA) and the Electron-Positron Coincidence Experiment) planned for the newly completed Experimental Area IV. In addition, significant effort was expanded on planning and design for GAMMASPHERE, a proposed National Gamma Ray facility, and on procurement of prototype detectors for this project. The layout and optics for the beam lines into the new Area IV were completed. The FMA Project is on schedule with the purchase order for the major ion-optical elements placed in the early summer of 1988, and designs for the support structure, scattering chamber, and focal-plane area are well under way. An FMA Steering Committee was formed to provide information regarding the priorities of researchers who plan to use the device. The FMA is expected to be assembled, tested and calibrated early in 1990. Significant effort was spent on evaluation of various possible designs for the overall detector system for the Electron-Positron Coincidence Experiment and establishing the feasibility of using silicon detectors to provide the energy and timing resolutions needed. The details of this work are given in Section I.E. Work continued on the expansion of the capabilities of existing experimental stations. Work has been done on design studies of detectors for the proposed GAMMASPHERE. Orders have been placed for a prototype Compton-Suppressed Ge Detector with a delivery date early in 1989, and for BGO detectors with a delivery date of summer 1989. These detectors will be evaluated in tests at ATLAS as soon as they arrive. The first particle-gamma coincidence measurements using a newly constructed chamber were successfully performed. The final chamber configuration is expected to be completed early in 1989. A new timing detector to be used to define the beam-pulse timing characteristics of beams from the new ECR source was designed, fabricated, and successfully tested.

a. Fragment Mass Analyzer Project (C. Davids, B. Back, R. Betts, D. Kovar, and W. Kutschera)

The procurement process for the main ion-optical elements of the FMA was completed in the early summer of 1988. After requesting bids from 15 vendors, the contract to construct the two electric dipoles, one 40° bending magnet, two quadrupole doublet magnets, power supplies for the magnets, and one nuclear magnetic resonance probe was awarded to Bruker Analytische Messtechnik in Karlsruhe, FRG. This company also built the ion-optical elements for the RMS at the Laboratori Nazionali di Legnaro in Italy. The order was placed in early July 1988, with delivery expected in the summer of 1989.

In April 1988 a FMA Users Workshop was held, with approximately 20 attendees. A FMA Steering Committee was chosen, consisting of A. Ramayya, Chairman (Vanderbilt U.), J. Kolata (Notre Dame), C. Lister (Yale), W. Walters (Maryland), and N. Koller (Rutgers). This committee will oversee the FMA project and provide advice on the experimental equipment to be provided for the FMA. At the workshop, a number of university users agreed to take on the development of various detectors for the FMA. These include a 16-counter neutron array for the target area (Vanderbilt, LSU, Florida), a thin-scintillation focal-plane detector (Florida, Vanderbilt), a Bragg-curve spectrometer for the focal plane (Notre Dame), and a nuclear spectroscopy/nuclear moments facility behind the focal plane (Rutgers, Weizmann). These university projects are proceeding, with the goal of having the detectors ready for experiments in early 1990.

The final design for the FMA support structure is currently being completed. Information on the interfaces of the ion-optical devices and the support has been received from the manufacturer, and the procurement process for the support will begin in early 1989.

In the fall of 1988 the ATLAS target room addition was completed. The utilities for this structure will be installed in 1989, and the FMA support structure will be installed about the same time, when the ATLAS target room crane can be positioned in the new addition.

Electrostatic calculations for the electric dipoles were carried out, using the program POISSON. The results show that a simple field clamp at entrance and exit ports of the vacuum tank can define the fringe fields and the bending angle of the deflector. These results have been incorporated in the design of the dipoles by the manufacturer.

The properties of the FMA have been presented at a number of international meetings, and the device has been received with enthusiasm. A number of other laboratories are proposing to construct nearly identical facilities. These include the KVI at Groningen, the Netherlands, and the Nuclear Science Centre at New Delhi, India.

b. Beamline System to the FMA and the New Target Area (W. Kutschera, R. Kickert and J. Specht)

The anticipated main use of the FMA will be at zero degrees with respect to incident beam direction. This requires a very "clean" tuning of the beam to the FMA target. Ample provision of beam steerers and remotely-controllable slit systems will facilitate this task. A set of four quadrupole lenses will be used to focus the beam with almost any desired shape onto the FMA target. Calculations of the beam optics from the exit of ATLAS to the FMA target were performed with TRANSPORT.

Beams from ATLAS will be distributed by a switching magnet to the FMA (10-degree bend) and to another major piece of equipment (possibly an electron-positron spectrometer) in the new target area. The location of the latter requires a bend of 33 degrees. An old cyclotron model magnet used many years ago in the Chemistry Division of Argonne, with a diameter of 28 inches and a maximum field of 1.7 T, will be used for this purpose. The magnet has been tested and found to function satisfactorily. It will bend uranium beams of more than 6 MeV/amu to the 33-degree beamline.

For the new beamline systems, a shielding scheme with concrete blocks available on site has been designed, which will allow access to most target areas not fed by the beam from ATLAS. The FMA beamline is expected to be ready to deliver beams from ATLAS to the FMA by the end of 1989.

c. Development of Vacuum-Mounted High-Voltage Power Supplies for the FMA (C. Davids, J. Bogaty, B. Nardi, W. Kutschera, S. Haase*, and C. Shaffer†)

The two prototype 300-kV power supplies have been tested in vacuum, and under beam-bombardment conditions. With both supplies in place, connected to round aluminum electrodes, a total voltage of 480 kV (240 kV on each supply) was achieved across a 9.4-cm gap. This corresponds to a field strength of 51 kV/cm. The design values for the FMA are a total voltage of 450 kV across a 10-cm gap, yielding a field strength of 45 kV/cm.

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*Student from Eastern New Mexico University, Portales, NM.
†Student from Hope College, Holland, MI.

In the beam test, an aluminum electrode was mounted on the positive power supply and placed in the 36" scattering chamber. A 50-nA beam of 70-MeV carbon ions was allowed to stop in the electrode. The electrode voltage was observed to remain constant to within a few parts in 100,000. The supply current to the electrode dropped by 50 nA during the bombardment, as expected.

During the vacuum tests of the power supplies, the PVC plastic enclosures were observed to become discolored during high-voltage conditioning. It has been determined that this discoloration is on the surface, and is due to damage caused by electrons, not photons. In the FMA electric dipoles, ceramic enclosures will be used, and electron damage is not expected to be a problem.

A computer program is being developed to control and monitor the power supplies. It will also allow automatic high-voltage conditioning. This program will be expanded to include control and monitoring of the magnet power supplies as well.

d. Development of a Sliding-Seal Scattering Chamber for the Fragment Mass Analyzer (B. B. Back, C. N. Davids and J. Falout)

The Fragment Mass Analyzer has the feature that it can be rotated in the angular range from -5° to +45°, which is especially useful for detecting reaction products other than evaporation residues from complete fusion reactions. In order to take advantage of this feature in an efficient way, a small scattering chamber, which is able to accommodate this motion, is presently being designed. The chamber has an inner diameter of 39.5 cm, which represents the largest diameter commensurate with the distance of 30 cm from the target to the effective field boundary of the first quadrupole of the FMA. The chamber is rigidly attached to the support frame of the FMA, which means that the beam enters the chamber through a sliding-seal port with the necessary 50° angular travel. The chamber is designed to accommodate two independently-rotatable rings for mounting small detection systems inside the chamber. A large 30 x 30 cm^2 port on one side of the chamber allows for the measurement of coincident binary products in cases where the FMA is positioned away from 0°. Other ports are included in the design in order to insert the target-ladder/wheel assembly and charge-state resetting foil. Pumping ports and view ports are also provided.

e. Design Study for a Rotating Target Wheel (B. B. Back, J. Done, and H. Esbensen)

In order to be able to utilize the high beam currents expected from the upgrade of the ATLAS facility with the addition of the Positive Ion Injector it is necessary to develop target facilities, which are able to withstand the increased beam intensity. This is particularly important for the Fragment Mass Analyzer facility, which is able to separate rare reaction products from the copious elastically scattered beam particles, particularly at forward angles. The initial phase of this project involves the development of a computer program to calculate the temperature distribution of targets mounted at the periphery of a rotating target wheel. The power imparted to the target material by the energy loss of the beam passing through the target is dissipated by way of black-body radiation and to a minor extent by heat transport through the target foil. Such calculations allow for the determination of the maximum temperature of the target foils as a function of the beam intensity and species, target material and thickness, as well as the wheel diameter and rotational frequency. The objective is to rotate the wheel at a frequency sufficient to keep the maximum temperature well below the melting temperature of the target material.

As a result of the calculations, it appears that a target wheel of about 15-20-cm diameter rotated with angular frequencies up to 1000 R.P.M. will satisfy the requirements for most experiments. The design of similar target wheels used at accelerators with less than 100% duty cycle, such as the UNILAC at G.S.I., is complicated by the fact that the rotational frequency and phase of the wheel must be synchronized with the macro-structure of the beam in order to avoid the beam striking the target frames. At ATLAS, which is a 100% duty-cycle machine, we do not have this problem. Instead of synchronizing the wheel rotation to the macro-structure of the beam, we propose to synchronize the beam to the target-wheel rotation. This is easily achieved by providing a TTL signal from the target wheel assembly, which is used to drive the slow beam sweeper and turn the beam off when a target frame passes through its path. This method has the advantage of being able to set the rotational frequency of the target wheel according to the experimental conditions and not being dictated by the macro-structure of the beam.

A further refinement, which is planned, is to provide an angular decoder indicating which target is being bombarded at any particular instant. By reading out this decoder as part of the event structure in on-line experiments, it is possible to run control experiments simultaneously by mounting different targets on the target wheel. This is foreseen to be extremely useful in searches for very rare reaction products. In such experiments it can be verified that the correct experimental conditions exist by running a simultaneous control experiment, which yields similar reaction products at a higher rate.

f. Design of a FMA Focal-Plane Detector (D. G. Kovar, and D. J. Henderson)

A low-pressure, position-sensitive Parallel-Plate Avalanche Counter (PPAC) is being fabricated for use in the FMA focal plane. The detector, with an active area of 5 x 15 cm, is designed to provide x-y position resolutions of $\lesssim$ 1 mm and timing resolutions of $\lesssim$ 500ps. Operating with gas pressures of 1-2 Torr and front and back gas windows of the order of 75 $\mu g/cm^2$, the detector is anticipated to be used as a transmission detector in a large class of FMA experiments (i.e., as a position-defining diagnostic detector or as part of a detector system where it is backed by a silicon detector, Bragg Curve Spectrometer, etc.). The detector is expected to be operational by the end of the year.

g. The Argonne-Notre Dame BGO Gamma-ray Facility at ATLAS
(R. V. F. Janssens, T. L. Khoo, I. Ahmad, E. F. Moore, P. Wilt, K. Beard*, U. Garg* and M. W. Drigert†)

The construction of a gamma-ray facility, which consists of (a) a 4π gamma-sum/multiplicity spectrometer with 50 BGO elements and (b) 12 Compton-suppressed Ge detectors (CSG) external to the hexagonal elements was completed at the end of 1987. However, during this past year the effort related to this facility has continued on several fronts:

- -- A spare Ge detector was delivered and tested.
- -- Construction and testing of logic delay units for the inner array has been completed.
- -- A Camac unit for decoding the gamma-ray multiplicity is under design.

*University of Notre Dame, Notre Dame, IN.
†I.N.E.L., Idaho Falls, ID.

-- Several commercially available fast amplifiers which could be used as replacement units in the electronics of the array have been evaluated. None of the existing units satisfies our requirements and the possibility of developing a multi-channel amplifier in-house is now being considered.
-- A special target chamber for g-factor measurements was constructed, tested and successfully used in an experiment described elsewhere in this report.
-- A BaF_2 detector which fits in the BGO Compton-suppression shields was purchased. Its response in suppressed and add-back mode was evaluated.
-- The multiplicity and sum-energy response of the inner array was measured with a variety of γ-ray sources and the results were compared with Monte-Carlo simulations.
-- A variety of computer programs were developed in order to facilitate the setup of the various parameters of the array (gains, constant-fraction thresholds and walks, high voltages, etc.).

The facility was used successfully in a large number of experiments over the year, both in stand-alone mode and in conjunction with particle detector arrays. Design studies on the coupling of the gamma-ray facility with the FMA have just started and will be pursued vigorously in the coming year.

h. Detector Design Studies for National Gamma-Ray Facility and Proposal Preparation (T. L. Khoo, R. V. F. Janssens, I. Ahmad and T. Moog)

A proposal has been submitted to DOE for GAMMASPHERE, a National Gamma Ray Facility consisting of 110 Ge detectors with BGO Compton-suppressors. This detector system combines calorimetric and multiplicity information with the excellent energy resolution, large efficiency and high granularity of the Ge detectors. The large number of Ge detectors are essential for high- (3 or higher) fold coincidences. Since each additional fold results in roughly an order-of-magnitude improvement in selectivity, this feature makes it possible to cleanly isolate weak structures, where new physics will undoubtedly lie.

The Physics Division fully supports GAMMASPHERE. ATLAS, which will have the capability to produce both the lightest and heaviest beams, is an ideal accelerator to couple to this facility and space can be made available adjacent to the new Target Area IV.

In preparation for final design selection and construction of GAMMASPHERE, at Argonne we have undertaken to design, develop and construct a prototype detector module, consisting of a large n-type Ge detector and BGO elements for the suppression shield. This activity is being supported by the Argonne Laboratory Director's Exploratory Research Funds.

A prototype 70% n-type Ge detector has been ordered and delivery is expected in early 1989. The requirement of supporting a heavy Ge crystal with minimal surrounding material (to enhance Compton-suppression) has entailed radical departures from conventional designs. Design of the BGO Compton-suppression shield (which also serves for sum energy and multiplicity measurement) was undertaken in collaboration with the GAMMASPHERE Steering Committee. We also collaborated with physicists at Notre Dame on Monte-Carlo calculations of the detector response in order to decide on the optimum detector configuration. The present design uses significantly smaller BGO elements than first anticipated in the GAMMASPHERE proposal, which will result in reduced costs. Procurement of the BGO detectors has been initiated at Argonne, with delivery of detectors expected in summer 1989.

We have also been actively engaged in efforts to improve the chances of successful funding of GAMMASPHERE, for example in extensive preparations for a DOE technical and cost review of the project, and through activities of the Steering Committee which consists of D. Cline (Rochester), D. B. Fossan (Stony Brook), T. L. Khoo (ANL), I. Y. Lee (ORNL) and F. S. Stephans (LBL).

i. Test of a Barium-Fluoride-BGO Sum Spectrometer (I. Ahmad and T. L. Khoo)

Because of their high density, bismuth-germanate crystals can be made into compact detectors for the measurement of high-energy gamma rays. However, these detectors have timing characteristics which are not sufficiently good for differentiating gamma rays from neutrons. On the other hand BaF_2 crystals have very fast timing but low density. Thus a combination of BaF_2 and BGO crystals, with energies summed, will provide a detector with fast timing to distinguish gamma rays from neutrons, relatively small size and good peak/total performance.

A 6.25 cm X ܀.25 cm BaF_2 crystal was placed inside a BGO detector which is normally used as a Compton-suppressor shield for Ge detectors in the Argonne-Notre Dame Gamma Facility. An Amperex XP2020Q photomultiplier was used with the BaF_2 crystal. With a ^{88}Y source, peak/total ratios (where peak area represents the sum of the 898 and 1836 keV peaks) were measured in different modes. In the singles, Compton-suppressed and sum modes the peak/total ratios were 0.35, 0.65, and 0.54, respectively. The count rate in the 1836-keV photopeak for the three modes were in the ratio of 1:1:2.4. Thus, for a small reduction in peak/total ratio, a 2.4-fold increase in efficiency can be obtained in the sum mode with respect to the Compton-suppression mode. Further tests are in progress.

j. Scattering Chamber for the Argonne-Notre Dame γ-Ray Facility (S. J. Sanders, J. Falout, R. V. F. Janssens, and T. L. Khoo)

A large-particle scattering chamber is being constructed for performing particle-γ coincidence measurements at the Argonne-Notre Dame γ-ray facility at ATLAS. This chamber makes it possible to obtain high-quality particle spectra, with good angle and time-of-flight resolutions, in coincidence with γ-rays detected in the array. The main vacuum vessel and mounting framework have been assembled, tested, and used in several experiments described elsewhere in this report. For these experiments, a target assembly and a variety of detector mounts have also been constructed. Design work on an extension to the chamber which allows several large gas counters to be mounted within the vacuum vessel has been completed. The construction is well underway and it is anticipated that this extension will be available for experiments during the spring of 1989. Meanwhile, modifications to the existing support frame and to the target assembly are being prepared in order to increase flexibility in usage of the system.

k. Development of a Fast-Beam-Timing Detector (B. D. Wilkins, D. Henderson, B. B. Back, L. M. Bollinger, P. DenHartog, B. G. Glagola, D. Kovar and R. Pardo)

The new Positive Ion Injector presently being built for ATLAS will provide a substantial increase in both the mass and intensity of beams available from the facility. In order for the Injector Linac to operate satisfactorily it is necessary to inject beam pulses with well determined characteristics from the ECR source which is located on a platform at a +350-kV potential. One of these characteristics is the time structure of the beam, which should be such that the majority of the beam particles are bunched into narrow time peaks of less than 1-ns width. The fast-beam-timing detector must be able to monitor the width and phase of the beam bunches without distorting the main fraction of the beam being injected into the linac.

The present design is based on a thin tungsten (W) wire (~ 10μm diam.) mounted perpendicular to the beam intersecting only a very small fraction, typically less than 1%, of the beam particles. Electrons emitted from the surface of the wire (where the beam particles impinge) are accelerated toward the wall of a cylinder centered around the wire. A micro-channel plate assembly (viewing the wire through a rectangular aperture in the cylinder wall) detects and amplifies the electrons, producing a fast risetime signal, ideal for time-of-flight measurements. It is expected that this type of detector will live up to the requirements of little interference with the beam and excellent time resolution necessary to control the beam preparation for the injection linac.

ℓ. Measurements of Pulse-Height Defects and Plasma Delay Effects in Silicon Detectors (D. G. Kovar, B. Glagola, D. J. Henderson, R. Pardo, B. D. Wilkins, M. A. McMahan*, F. Prosser†, and G. J. Wozniak*)

The study of Pulse-Height Defect (PHD) and Plasma-Delay (PD) effects of heavy ions in silicon detectors begun last year with measurements at the 88-inch LBL cyclotron was continued this year with measurements at ATLAS. At the 88-inch cyclotron, the energy and timing response of ^{18}O, ^{36}Ar, ^{40}Ar, ^{63}Cu, and ^{86}Kr ions at 4 energies in the energy range $0.5 < E_{lab} < 10$ MeV/u had been measured. In the ATLAS measurements a seven-element ion-implanted strip detector was added to the detectors tested at LBL (i.e, surface-barrier, partially-depleted fission, diffused-junction, ion-implanted, and lithium-drifted detectors). The detectors were sequentially rotated to a forward angle ($\theta_{lab} = 7^{o}$) to detect the ions elastically scattered from a thin gold target. A micro-channel plate - micro-channel plate system was rotated into position for measurement of the ion's time of flight (velocity). Thus far measurements for ^{11}B, ^{16}O, ^{58}Ni, ^{76}Ge, and ^{109}Ag ions at 3-5 energies in the energy range $0.5 < E/A < 8$ MeV/u have been performed. The motivation for the present measurements was the need for data at energies $E > 1$ MeV/nucleon. The existing parameterizations of both PHD and PD effects are based on data at lower energies and are extrapolated to the higher bombarding energies. The results obtained thus far indicate that at energies $E > 2.0$ MeV/nucleon the energy dependence of the PHD's for the lighter-mass ions ($A < 60$) is rather flat, but for the heavier-mass ions ($A > 60$) the PHD increases rather significantly with energy. None of the existing PHD parameterizations are capable of reproducing the set of data obtained; the Kaufman parameterization reproduces best the magnitude and energy dependence for the lighter mass ions, while Moulton and Ogihara reproduce better the PHD behavior of the heavier mass ions. More measurements to complete the study are planned in the next year.

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m. <u>The New Focal-Plane Detector for the Split-Pole Spectrograph</u> (K. E. Rehm and F. L. H. Wolfs)

The new focal-plane detector consisting of a position-sensitive parallel-plate avalanche counter (PPAC) and a large Bragg-curve detector (BCD) has been successfully used in a variety of experiments requiring good mass and Z-resolution. The following resolutions were measured: M/DM = 150:1, Z/DZ = 70:1, E/DE = 200:1. The intrinsic time resolution of the detector was Dt = 250 ps, position resolution Dx = 0.75 mm, and angle resolution 0.8°. A paper about this detector has been published in Nucl. Instrum. Methods. Figure I-20 shows a two-dimensional plot of Z vs q^2/m measured with the detector for the system ^{58}Ni + ^{60}Ni at E_{lab} = 500 MeV. The individual elements and isotopes are clearly resolved. Future plans include an improvement of the Z-resolution which is important when heavier beams from the new positive-ion injector are available.

n. <u>Development of a Large-area Detector for Multiparticle Coincidence Experiments</u> (R. R. Betts)

Several recent experiments have shown interesting nuclear-structure features in the breakup of projectiles such as ^{24}Mg, ^{28}Si, ^{32}S following inelastic scattering and transfer reactions. These experiments require the coincident measurement of energy and angles and identification of binary fragments such as ^{12}C, ^{16}O at forward angles. To date the experiments have been performed using conventional position-sensitive detector telescopes which have the disadvantage of extremely low (<1%) efficiency for detecting the events of interest. This low efficiency further complicates the extraction of quantitative information from these data since a knowledge of the efficiency, besides phase space, requires input on spins, angular correlations etc. which are not known.

We are constructing a large-area detector to measure these and similar processes with high efficiency and excellent energy resolution. The detector will consist of a number of silicon microstrip detectors stacked so as to provide ΔE,E and position information. Each detector will have its own dedicated electronics of a type developed collaboratively between the University of Edinburgh and the Rutherford Laboratory in England. These detectors will be used in experiments at ATLAS for which the new capability of high-intensity rare gas beams such as ^{20}Ne and ^{36}Ar will open up new possibilities.

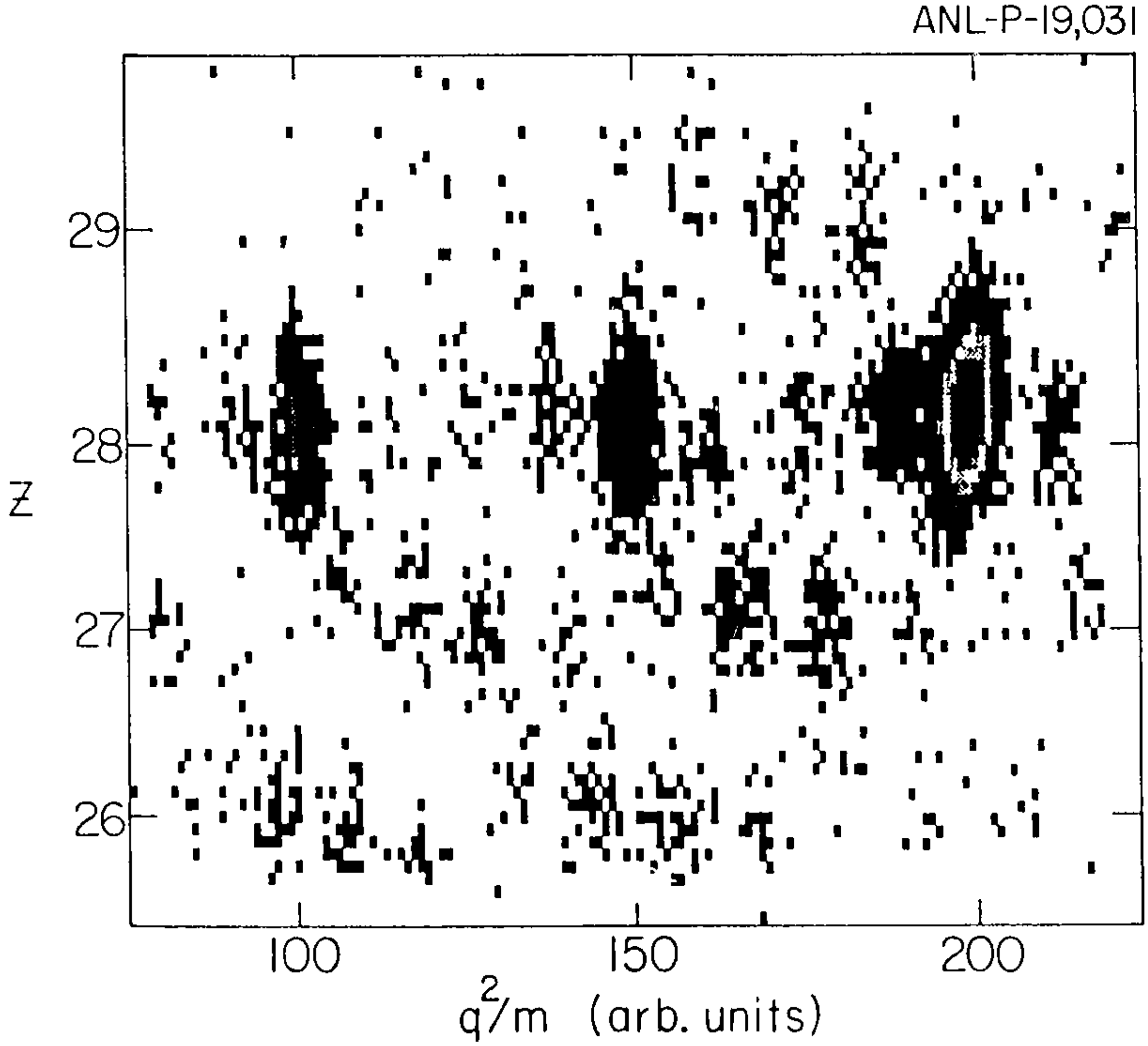

Fig. I-20. Two-dimensional plot of Z vs. q^2/m obtained with the new focal-plane counter from the system $^{59}Ni + ^{60}Ni$ at E_{lab} = 500 MeV and θ_{lab} = 10°.

o. Nuclear Target Development (J. P. Greene and G. E. Thomas)

The Physics Division operates a target-development facility which produces thin films for atomic and nuclear physics experiments, as well as for other scientific purposes. These services are available to the Physics Division, other Divisions of the Laboratory, and outside scientific institutions. In addition to the normal requirements, research is performed to develop new techniques for target fabrication as well as implementing advanced techniques developed elsewhere.

In the past year various targets were produced either self-supporting or on various substrates, stretched films and "sandwiched" foils. Targets produced included Al, Ag, Au, ^{11}B, ^{138}Ba, Bi, C, Cr, $^{74,76}Ge$, $^{154,160}Gd$, $^{24,26}Mg$, Mo, Ni, ^{208}Pb, Pt, $^{144,150,154}Sm$, $^{120,124}Sn$, Ta, Tb, $^{125,128}Te$, ^{232}Th, Ti, V, ^{186}W and Zr. Targets made from compounds were $^{180}HfO_2$, ^{6}LiF, Lu_2O_3, ^{24}MgO, PbF_2, $^{28}SiO_2$, TiO_2, UF_4 and WO_3. In addition, films of Formvar, Teflon PTFE and TFE were manufactured.

An NRC 3117 evaporator system, now in routine use, is our primary apparatus for either single or multiple resistively heated depositions. Included within this device is a Veeco Model VeB-6 electron beam gun. A second system, a Veeco Model VE-775 vacuum evaporator is now working and is mainly used for resistive evaporations. Within this apparatus resides an Ion Tech saddle-field sputter source which has been successfully employed for producing a number of targets. Future plans for this evaporator include the acquisition of a cryopump to replace the existing diffusion pump vacuum system.

Installation is continuing on the newly acquired Temescal four-pocket electron beam source within a third evaporator. This ultra-clean cryo-pumped system, coupled with this state-of-the-art electron beam gun will enable us to produce difficult, high-purity targets on a routine basis.

The continued upgrading of the above three systems has included equipping each with Kronos Model QM-331 quartz-crystal thickness gauges, for monitoring vapor deposition, and with thermocouple temperature sensors. These devices will now enable us to monitor a number of aspects of quality control in target production.

In addition to our vacuum evaporation systems, we are now routinely using our significant complement of auxiliary equipment. Among this is included a Frei & Borel type SE/EX rolling mill which is being used for simple rolled targets. Also, we are using our Lindberg Furnace, equipped with a gas manifold, for hydrogen reductions. A recently procured Forma Scientific Model 1854 laminar flow hood has provided us with additional clean bench space for producing difficult targets. An inert gas glove box has been installed and has been employed in the production of targets which may oxidize quickly.

The Target Laboratory now has numerous vacuum systems for the storage of fragile or vulnerable foils. One consists of a turbo-pumped chamber enclosing a rotating carrousel capable of holding up to 100 standard target frames. It is kept under vacuum (10^{-7} Torr) by active computer control. This system has been working without failure. A second, quite similar system has been recently constructed, although not under computer control, and is now fully operational. This chamber will be used for routine storage of hydroscopic and slowly oxidizing targets for extended periods of time.

Future plans include the installation of a recently acquired mass isotope separator from the ANL Chemistry Division. We are looking into the possibility of putting this device into operation for the production of highly enriched targets.

Also, investigations are continuing on the construction of a rotating target wheel evaporator system for the production of uranium foils. This may be implemented in conjunction with a dedicated low-level radioactivity target facility.

Other areas of long-range development include construction of an alpha-gauge thickness monitor. Also, cost evaluations have been made regarding a large state-of-the-art sputter source. This acquisition, if pursued, may require a new dedicated evaporator system. A laser beam system for the evaporation of metals, and especially, oxides of metals is an exciting new field of research which warrants further investigation.

p. Physics Division Computer Facilities (T. H. Moog, D. R. Cyborski, L. C. Welch, G. Perschbacher, and L. Budrik)

The VAX-780 continues to serve as the hub for Division computing. It serves as a node on the Argonne DECnet, on BITNET, on HEPNET, and as a routing node for the Physics Division DECnet linking 6 VAX and several PDP together. An RA81 and a used RP07 from the Argonne CMT Division have been added to the 780, increasing disk capacity by about 1000 Mbytes to about 2200 Mbytes. Additional laser printers have been installed because of the heavy use of the 780 for word processing. There are now nine laser printers connected to the 780. An 8mm helical-scan tape unit has been in use for disk backup since September, and has been successfully used for replay of data.

The three VAX-750s in the Division have continued to be reliable machines. The Dynamitron VAX is routinely used for data acquisition and replay. The ATLAS VAX provides data acquisition for two users of the ATLAS accelerator, as well as replay when CPU time and memory is available. The medium-energy VAX is used for the analysis of data from SLAC and BNL. It has been removed from the truck trailer, where it was kept for ease of shipment to SLAC and other sites, to a room in the Division. The Argonne members of BNL experiment E802 have installed and are using a Fermilab ACP computer system with 10 processors on the medium-energy VAX.

Two MicroVAX II are in the Division. Both MicroVAX II have had their disk capacity doubled to approximately 700 MBytes. The MicroVAX in the ATLAS data room is used for data acquisition and replay. The second MicroVAX is used by the weak-interactions group for analysis of LAMPF neutrino oscillation data.

It has been upgraded to an 8-user license from a 2-user license. A Daphne data acquisition system is being built for use with it. The weak-interactions group has purchased four VAXstation 2000 and one VAXstation 3200 which they plan to join into a local-area-VAXcluster, along with the existing medium-energy VAX-750 and the weak-interactions MicroVAX.

Funds have been budgeted for the purchase of three VAXstation 3500's for replay of data.

All PDP-11/45's, used with the previous generation data-acquisition system, have been decommissioned.

q. The Data-Acquisition System DAPHNE (T. H. Moog, D. R. Cyborski, L. C. Welch, G. Perschbacker, and L. Budrik)

DAPHNE, the data-acquisition system developed for ATLAS, is routinely used for experiments at ATLAS and the Dynamitron. Enhancements during the past year include the following: ability to create "reduced event tapes", ability to drive two graphics devices simultaneously, and allowance for users to integrate their own histogram operations into the DAPHNE. Changes were made to the internal organization of DAPHNE so that people could install DAPHNE at other sites without special operating system privileges. It is expected that this will make DAPHNE easier to export to other institutions. The "User's Guide to DAPHNE" was completed and printed.

E. P. Kanter has successfully used DAPHNE to acquire data from a hybrid Fastbus/Camac system at the Dynamitron. He is also working with R. T. Daly of the Electronics Division to develop Fastbus modules in order to produce a purely Fastbus acquisition system using DAPHNE.

r. Enhancement of Minority Involvement in DOE Nuclear Physics Programs
(B. Zeidman)

The primary objective of the program is to generate an increase in the level of minority involvement in nuclear physics by actively interacting with a substantial number of minority students and faculty members. The basic problem is to identify, stimulate, and motivate both faculty and students to take advantage of existing programs that will involve them in nuclear physics. With the assistance of Professor Warren Buck of Hampton University, a program has been initiated to address each aspect of the problem.

Contact has been made with Physics Departments of a number of minority institutions that have a history of programs in physics and, in addition, several universities with large minority enrollments. Information has also been sent to the recipients of APS Minority Scholarships. Visits to a number of minority institutions have been scheduled for the early part of CY 1989, the period when many of the summer programs require completed application forms. DEP at ANL has agreed to be quite flexible with closing dates for minority applicants. During the visits there will be presentations, e.g. seminars, and discussions with both students and faculty. It is hoped that this direct personal contact will be a stimulus for increased interest in physics, and particularly nuclear physics. An effort will be made to motivate students and faculty to consider summer appointments or possible short visits to the Laboratory. An innovative accelerator-based physics training program that will utilize the 2-MV Van de Graaff is a possible way to accomplish this.

While the "recruiting" part of the program will take a recess by late March, efforts will be continued during meetings throughout the year, e.g. APS, AAPT meetings. In line with this, a booth was set up at the meeting of the Society for the Advancement of Chicanos and Native Americans in Science, San Jose, January 1989.

We hope that the initial contacts established during FY 1989 will be continued and broadened during subsequent years. It is expected that such ongoing interactions will, in time, generate interactive relationships that will enrich the physics programs at minority institutions and substantially enhance minority involvement in nuclear physics.

II. OPERATION AND DEVELOPMENT OF ATLAS

This activity consists of both the operation and the upgrading of the Argonne Tandem-Linac Accelerator System (ATLAS) so as to provide beams of heavy-ion projectiles for research in nuclear physics and occasionally in other areas of science. Approximately half of the running time is allocated to outside users. The accelerator system, whose layout is shown in Fig. II-1, now consists of a 9-MV tandem injector and a linac with 42 superconducting RF accelerating structures. This system provides projectiles with energy >5 MeV per nucleon for ions with mass A < 100. In order to extend the mass range up to uranium and increase the beam intensity by a large factor, we have undertaken a 3-phase project aimed at replacing the tandem injector and its negative-ion source with a new class of superconducting-linac injector and an ECR positive-ion source. The first phase of this new injector system has been successfully tested and will go into operation on a scheduled basis in mid 1989.

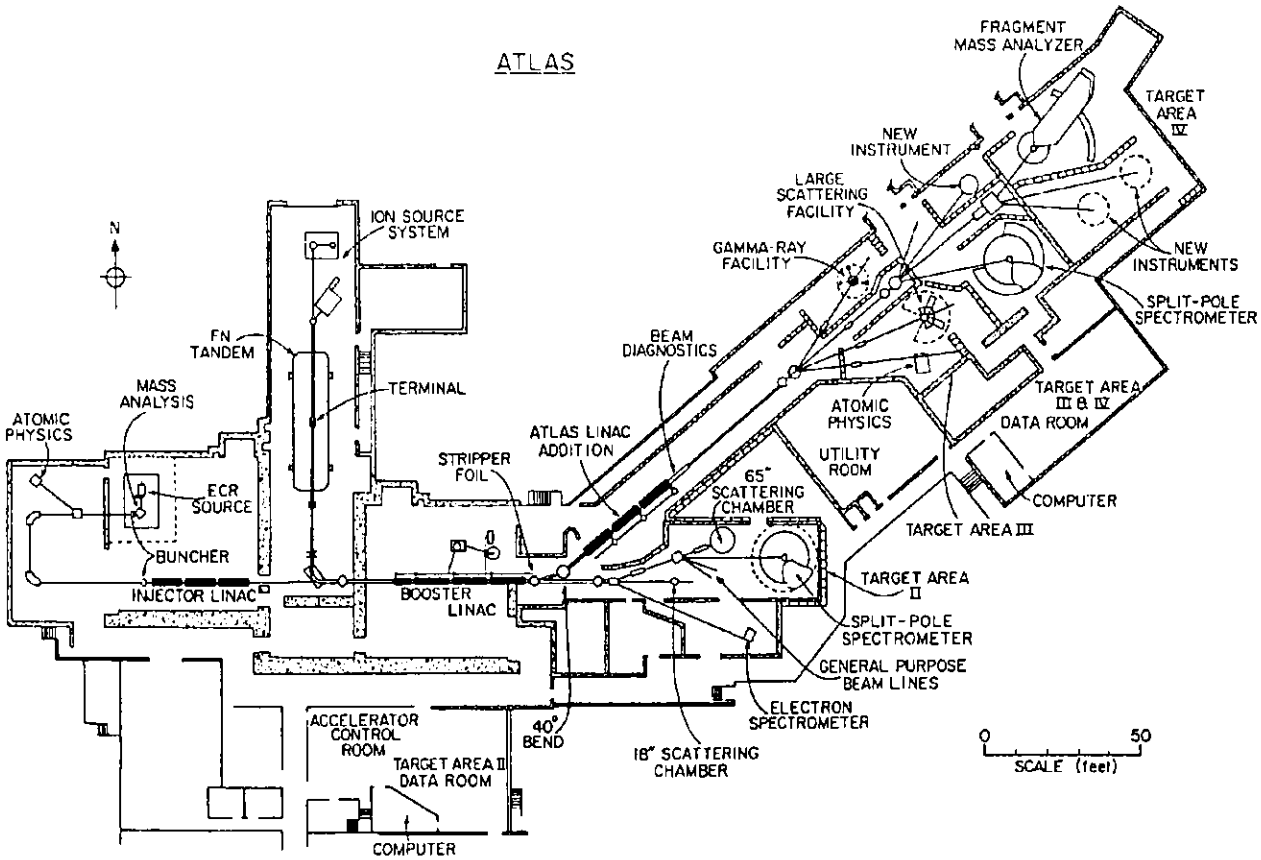

Fig. II-1. Layout of ATLAS. The system in use until May 1989 has consisted of the tandem injecting into the "booster" linac followed by the "ATLAS" linac. The new positive-ion injector, of which the first phase will be ready for use in May, is shown on the left side of the figure.

A. OPERATION OF ATLAS

(P. K. Den Hartog, S. L. Craig, R. E. Harden, D. V. Hulet, F. H. Munson, Jr., B. H. Orszula, I. R. Tilbrook, and G. P. Zinkann)

The first ion beam was accelerated through a section of the ATLAS linac on June 28, 1978. Since that first proof-of-principle experiment, the size of the linac has been expanded year by year as more accelerating sections became available, and at each step of the way the tandem-linac system has been used regularly for physics research. This operating history is summarized in Fig. II-2. Note that the accumulated beam time of ATLAS is now more than 35,000 hr., substantially greater than for any other superconducting accelerator of ions.

During FY 1988 ATLAS was operated on a regular schedule of 5 1/2 days of running time per week. In addition to this scheduled time, the operation was often extended through the weekend if needed to make up for the loss of scheduled running time during the week. As a result of these extensions, almost all scheduled users got the amount of running time that the PAC has authorized.

During FY 1989, fiscal constraints have made it necessary to reduce the operating schedule to 5 days per week, and only rarely can the running time be extended through the weekend. Moreover, the operating schedule needs to be interrupted for two periods of about 5 weeks each because of activities associated with the installation and startup of the Phase I positive-ion injector. The combined effects of these factors will cause ATLAS to have a substantial reduction in useful operating time in FY 1989. Some statistics concerning the operation of ATLAS are given in the following table.

Distribution of Machine Operation (hr)	FY 1988	FY 1989	FY1990	FY1991
Research	3648	3000	3800	4500
Tuning	1265	1050	1000	1000
Machine Studies	221	450	350	350
Unscheduled Maintenance	912	750	800	800
Scheduled Shut Down	2738	3510	2810	2110
Total (1 year)	8784	8760	8760	8760

ATLAS EXPERIMENT SUMMARY

Beam Use for Research (hr)				
Nuclear Physics	3,302	2,700	3,450	4,050
Atomic Physics	312	250	300	350
Other	34	50	50	100
Total	3,648	3,000	3,800	4,500
Number of Nuclear Experiments Receiving Beam	41	34	45	47
Number of Scientists Participating in Research	107	100	140	150
Outside Institutions Represented				
Universities (U.S.A.)	14	14	18	20
DOE National Laboratories	2	2	2	2
Other	10	10	10	11
Usage of Beam Time (%)				
In-House Staff	49	48	44	43
Universities (U.S.A.)	42	42	46	46
DOE National Laboratories	1	2	2	2
Other Institutions	8	8	8	9
Total	100	100	100	100

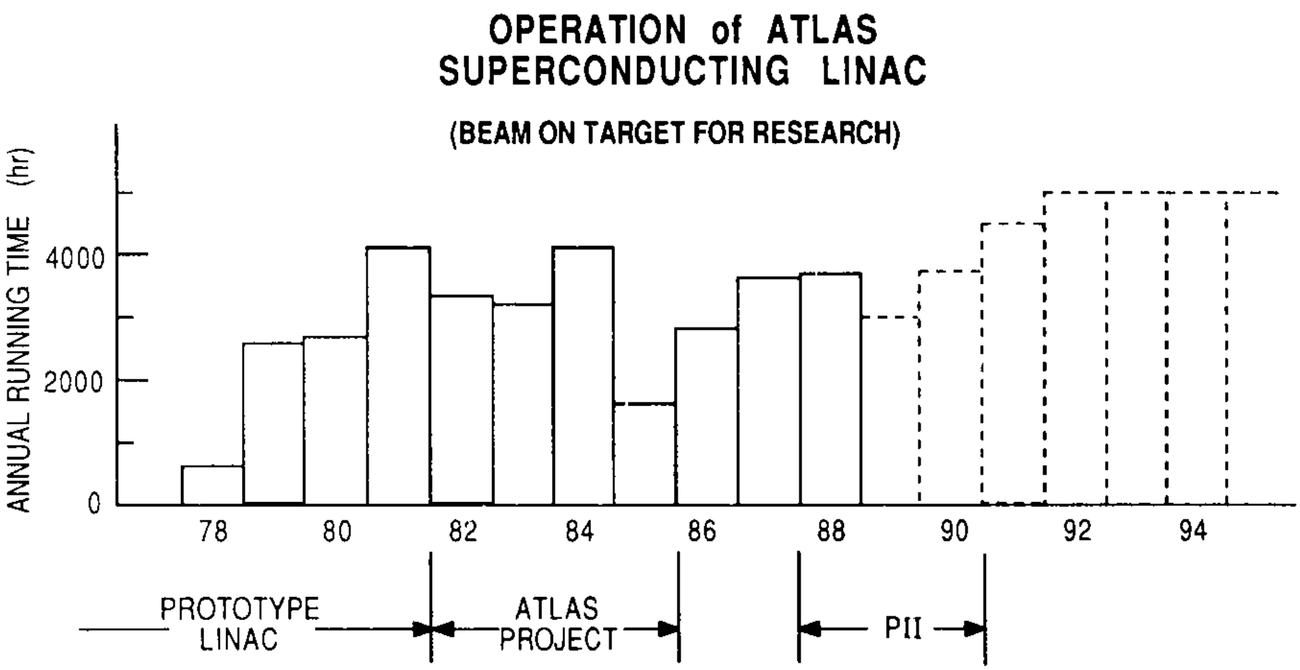

Fig. II-2. Summary of running time of the ATLAS superconducting linac. Note the sharp dips in running times in 1985 and 1989 caused by the installation of major new accelerator components.

We are now entering a period when two entirely different kinds of ion sources will be available for injection into the ATLAS linac: the negative-ion source of the original tandem injector and the positive-ion ECR source followed by the superconducting-linac injector described in some detail in I. Except for some short tests of the Phase I positive-ion injector (PII-1) during February-March 1989, ATLAS will be operated as a tandem-linac system until mid 1989. Thereafter, for the remainder of 1989, PII-1 and the tandem will be used alternately as the injector for the ATLAS linac, depending on user requirements. Generally speaking, the tandem will be used when maximum beam energy is needed, whereas PII-1 will be used when large beam currents are required or when the user wants ion species that cannot be made easily with the negative-ion source of the tandem. The initial use of PII-1 will probably concentrate on the acceleration of the noble gases with A < 100, on the isotopes of calcium, and on a few other nuclear species with A < 100. It will take time and effort to develop a large number of other beams.

Looking further into the future, in 1990 we expect to be able to expand gradually the operating schedule of ATLAS up to 7 days per week, thus substantially increasing the annual beam time. The research capability of ATLAS will also be expanded greatly in 1990, first by putting the Phase II positive-ion injector into operation in early 1990 and then by completing the last phase of the PII project in late 1990. The Phase II system will expand the mass range of projectiles from ATLAS up to at least A = 190, and the final PII will allow ATLAS to accelerate atoms of all masses. These two installation and commissioning periods will, of course, limit running time somewhat during 1990.

B. RECENT IMPROVEMENTS IN ATLAS

ATLAS is a well-developed accelerator that is being used routinely as a research tool. Nevertheless some parts of the accelerator are being improved, as outlined below. However, because of pressures connected with the PII project, during the past year the effort devoted to improving the present accelerator was much less than in the past. Almost no effort was devoted to the tandem except that required for the immediate research program.

Some of the topics mentioned below are discussed in greater detail in Sect. D.

Phase Stability of Resonators. As reported in 1988, for some time the operation of ATLAS has been plagued by occasional erratic changes in the phases of some resonators. After considerable effort, it was concluded that this problem resulted from defects in the distribution system for the master-oscillator reference signal. During the past year this system has been redesigned and replaced, and the phase-control problem has been eliminated. This improvement has had a considerable impact on operational efficiency because now the tune of a given ion species can be used repeatedly over a long period of time, and phases and amplitudes set on the basis of calculation are much more likely to be correct.

Refrigeration Capacity. The 100-watt helium refrigerator installed earlier for use with PII-1 continues to provide about 40 W of cooling for the present ATLAS linac. This small additional cooling has significantly increased the operational efficiency of the existing linac because it assures that all heat exchanges in the liquid-helium distribution lines can function properly.

Ion Source. A SNICS ion source has been put into operation at the tandem during the past year. This source has increased substantially the intensity of beams available from ATLAS for various ions such as calcium and titanium.

Beam Bunching. Excellent beam bunching continues to be of major importance to ATLAS users, and consequently the exceptional capability of ATLAS in this regard is being continually refined. During the past year the measured beam-pulse width at the scattering chamber in Area III was pushed down from 140 ps (FWHM) to 107 ps, which implies that the actual width is $<$ 95 ps. This new performance standard was achieved by refining the technique used to generate and distribute the reference zero-time signal.

Because of the interest in measuring time distributions that are less than 100 ps wide, one needs a rugged and reliable diagnostic detector that can rapidly establish beam-pulse characteristics with exceptionally good time resolution. A step in this direction is the new diagnostic detector described in Sect. I.F.k.

C. ASSISTANCE TO OUTSIDE USERS OF ATLAS
(Bruce G. Glagola)

The continuing strong interest in ATLAS (outside users were involved in over 70% of all experiments performed in 1988) makes it clear that the user-assistance program fills an essential function.

The outside user involvement continued to increase from that in 1987. A user liaison physicist continues to play a key role in channelling assistance to outside users. The major components of his responsibility are: (1) to provide the needed information and organizational assistance to committees, workshops, and other meetings involving outside users; (2) to provide users with technical information about ATLAS and its experimental systems, and to provide instruction in its use; (3) to assist outside users in all aspects of initiating and planning an experiment; (4) to the extent that is appropriate and feasible, to assist users in the actual performance of experiments; (5) to provide instruction and help with the use of computer hardware and software; (6) to instruct the users in the safety procedures to be followed when using the ATLAS facility; (7) to assist in the operation of the technical support group; and (8) provide an interface between the user, and the technical support and ATLAS operation groups.

The Program Advisory Committee (PAC) for ATLAS (having five members from other institutions and two from Argonne) continues to meet regularly during the year. PAC meetings were held on November 6, 1987, April 16, 1988, and October 22, 1988 to recommend experiments for running time at ATLAS. The present PAC members are Douglas Cline (University of Rochester), C. Lewis Cocke (Kansas State University), Robert Janssens (ANL), Peter Parker (Yale University) K. Ernst Rehm (ANL), Robert Vandenbosch (University of Washington) and Victor Viola (Indiana University). On the average, the PAC is asked to review 20 proposals for 90 days of running time per meeting. The demand for running time at ATLAS continues to be more than the available accelerator time.

The PAC meeting on 6 November was preceded on 5 November by an "open PAC" meeting that was attended by about 45 scientists. The open PAC meeting was held to give the PAC members a better understanding of the ongoing programs at ATLAS for both the outside and inside users. The Uranium Upgrade and plans to extend the experimental facilities at ATLAS were also discussed. The speakers at this year's meeting were L. M. Bollinger (ANL), J. J. Kolata (University of Notre Dame), R. V. F. Janssens (ANL), R. R. Betts (ANL), F. L. H. Wolfs (ANL), S. J. Sanders (ANL), B. D. Wilkins (ANL), W. Trzaska (Purdue University), W. Kutschera (ANL), J. LaVerne (University of Notre Dame), P. DeYoung (Hope College), A. E. Livingston (University of Notre Dame), and W. Phillips (University of Manchester).

The ATLAS User Executive Committee organized a User Group meeting during the April, 1988 APS meeting held in Baltimore. The meeting was attended by approximately 40 scientists. The main topics of discussion were the FMA project, the positive-ion-injector ATLAS upgrade and the proposed positron experiment at ATLAS. Nominations for an Executive Committee election were also taken at the meeting. The election was held during the summer. The new ATLAS Executive Committee consists of Jolie Cizewski (Rutgers University), as chairperson, James Kolata (University of Notre Dame), Akunuri Ramayya (Vanderbilt University), and William Walters (University of Maryland). Outside users are heavily involved in the Fragment Mass Analyzer. A collaboration of prospective users has been formed and a Steering Committee consisting of A. Ramayya, Vanderbilt University (Chairman), J. J. Kolata, University of Notre Dame, N. Koller, Rutgers University, C. Lister, Yale University, and W. Walters, University of Maryland, has been meeting periodically (April and November 1988) to help establish priorities in the experimental system. Members of the FMA collaboration are also participating in the construction of the detection system for the FMA, with a tape-transport system being developed by W. Walters, University of Maryland and J. Hill, Iowa State University, a neutron wall by A. Ramayya, Vanderbilt University, a Bragg-curve spectrometer by J. J. Kolata, University of Notre Dame; and a thin- film-fast timing detector by R. Piercey, Space Astromony Lab and M. L. Muga, Florida State University. For more details see section I.F., on the Fragment Mass Analyzer.

The prospect of uranium beams by late 1990 has brought about an ANL-FSU-MSU-Princeton-Yale collaboration to design and propose a positron experiment to investigate and resolve the question of "anomalous positron peaks" that have been seen at GSI. Six collaboration meetings were held to converge on an optimal design for the apparatus. A proposal for constructing such a device is being prepared for submission to DOE at the end of January 1989.

A major national initiative in low-energy heavy-ion research is the proposal for GAMMASPHERE. As is discussed in section I.F., Argonne has a major role in the scientific and technical activities that led to this proposal and the subsequent DOE technical and cost review. Argonne will procure, test and evaluate the prototype Ge and BGO detectors, which were designed in collaboration with the GAMMASPHERE Steering Committee, University of Notre Dame, and detector manufacturers. Should GAMMASPHERE be sited at ATLAS, this facility will certainly form a major focus of outside user activities. With GAMMASPHERE the scope and character of "Assistance to Outside Users" will be substantially modified in order to accommodate the changed user needs.

The magnitude of the outside use of the accelerator during the past year has been substantial, as may be judged from the following two lists giving (1) the experiments performed by outside users and (2) the institutions represented. As may be seen from the names associated with each experiment, university groups are 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 calendar year 1988 are listed below. The spokesperson for each experiment is given in square brackets after the title. The names in parentheses are Argonne collaborators.

(1) Temperatures and Level Densities of Highly-Excited Nuclei [Natowitz]
J. Natowitz, R. Schmitt, R. Wada, K. Hagel, Y. Lou, L. Cooke, H. Utsonomiya, Texas A&M University; G. Nebbia, G. Viesti, G. Prete, G. Nardelli, R. Zanon, B. Fornel, Laboratori Nazionali di Legnaro; P. Gonthier, Hope College; (B. D. Wilkins)

(2) Neutron-Rich Nuclei Produced in Multinucleon Transfer Reactions [Körner]
H.-J. Körner, University of Munich; G.-E. Rathke, GSI; (K. E. Rehm, F. L. H. Wolfs, C. N. Davids, R. V. F. Janssens)

(3) Development of a Radiocalcium Dating Method Using Accelerator Mass Spectrometry [Paul]
M. Paul, Hebrew University; (P. J. Billquist, B. G. Glagola, W. Kutschera, R. C. Pardo, K. E. Rehm, J. Yntema)

(4) Charged Particle Gamma-Ray Coincidences as a Probe of Nuclear Structure at High Spin [Betts]
M. Hass, University of Rochester; H.-J. Körner, University of Munich; G.-E. Rathke, GSI; M. Drigert, INEL; K. Beard, University of Notre Dame, (R. R. Betts, T.-F. Wang, R. V. F. Janssens, T. L. Khoo, E. F. Moore, S. J. Sanders, F. L. H. Wolfs)

(5) Spectroscopy of ^{56}Ni Fission Fragments [Sanders]
M. Drigert, INEL; (B. B. Back, R. R. Betts, R. V. F. Janssens, T. L. Khoo, S. J. Sanders)

(6) Test of dE-E Heavy Ion Detectors Using Thin Spin-Coated Fast Plastic on CsI [Norbeck]
E. Norbeck, University of Iowa; (D. J. Henderson, D. G. Kovar, B. D. Wilkins)

(7) Atomic Spectroscopy of Few-Electron Bromine [Livingston]
A. E. Livingston, A. Zacarias, Y. Lu, University of Notre Dame; (H. G. Berry, R. W. Dunford)

(8) Study of the Triaxiality in the Nucleus $^{221}_{91}$Pa [Ahmad]
M. Drigert, INEL; (I. Ahmad, R. V. F. Janssens, T. L. Khoo)

(9) Measurement of the Gamma-Ray Width of the 5.17-MeV State in ^{14}O [Parker]
P. Parker, P. Magnus, Yale University; (C. N. Davids, R. V. F. Janssens, K. E. Rehm, S. J. Sanders, T. F. Wang)

(10) Quasielastic Reactions of ^{28}Si with ^{208}Pb [Kolata]
J. J. Kolata, S. Dixit, R. Kryger, A. Morsad, University of Notre Dame; (K. E. Rehm, D. G. Kovar)

(11) Magnetic Moments of High-Spin Levels (Hass)
M. Hass, University of Rochester; H. J. Körner, University of Munich; G. E. Rathke, GSI; M. Drigert, INEL; (R. V. F. Janssens, T. L. Khoo, F. L. H. Wolfs)

(12) Measurement of the Gamma-Ray Width of the 5.17-MeV State in ^{14}O, Part II [Parker]
P. Parker, P. Magnus, Yale University; (C. N. Davids, R. V. F. Janssens, K. E. Rehm, S. J. Sanders, T. F. Wang)

(13) Investigation of Octupole Deformation in Th Nulcei [Habs]
D. Habs, Max Planck Institute; H. J. Körner, University of Munich; G. E. Rathke, GSI; M. Drigert, INEL; (R. V. F. Janssens, T. L. Khoo, F. L. H. Wolfs)

(14) Further Development of a Radiocalcium Dating Method Using Accelerator Mass Spectrometry [Paul]
M. Paul, Hebrew University; (P. J. Billquist, B. G. Glagola, W. Kutschera, R. C. Pardo, K. E. Rehm, J. Yntema)

(15) RDM Lifetime Measurements in $^{182,186}Pt$ [Garg]
U. Garg, K. Beard, D. Ye, University of Notre Dame; (I. Ahmad, R. V. F. Janssens, T. L. Khoo)

(16) Charge Collection in Si Multilayered Structures for ^{58}Ni and ^{63}Cu at 395 MeV [Stapor]
W. Stapor, A. Campbell, A. Knudsen, P. McDonald, Naval Research Laboratory; (B. G. Glagola)

(17) Measurement of Sub-Barrier Reaction Cross Sections Using the BGO-CSS Array [Betts]
C.N. Pass, Oxford University; J. S. Lilley, Daresbury; B. R. Fulton, University of Birmingham; (R. R. Betts, B. B. Back, R. V. F. Janssens, S. J. Sanders)

(18) Neutron-Rich Nuclei Produced in Multi-nucleon Transfer Reactions, II [Körner]
H.-J. Körner, University of Munich; G.-E. Rathke, GSI; (K. E. Rehm, F. L. H. Wolfs, C. N. Davids, R. V. F. Janssens)

(19) Coincidence Measurement of the Lifetime of the 2^1S_0 State in Helium-Like Ni^{26+} [Dunford]
M. Hass, University of Rochester; L. Curtis, University of Toledo; A. E. Livingston, A. Zacarias, University of Notre Dame; (H. G. Berry, R. W. Dunford, C. Liu, M. L. A. Raphaelian)

(20) Neutron-Rich Nuclei Produced in Multi-nucleon Transfer Reactions, III [Körner]
H.-J. Körner, University of Munich; G.-E. Rathke, GSI; (K. E. Rehm, F. L. H. Wolfs, C. N. Davids, R. V. F. Janssens)

(21) Lifetime of the $2S_{1/2}$ State of Hydrogen-Like Ni^{27+} [Dunford]
L. Curtis, Unversity of Toledo; M. Hass, University of Rochester; (R. W. Dunford, C.-J. Liu, M. L. A. Raphaelian)

(22) Radiation Chemistry Studies with Heavy Ions [LaVerne]
J. LaVerne, R. Schuler, R. Steinbeck, University of Notre Dame

(23) Measurement of Pulse Height Defects in Silicon Detectors [Kovar]
F. Prosser, University of Kansas; (D. G. Kovar, B. G. Glagola, D. J. Henderson, R. C. Pardo, B. D. Wilkins)

(24) Study of Shape Coexistence in ^{182}Hg [Ramayya]
A. Ramayya, J. Hamilton, S. Zhu, Vanderbilt University; P. Daly, M. Quader, Z. Grabowski, Purdue University; W. Trzaska, University of Jyvaskyla; (I. Ahmad, R. V. F. Janssens)

(25) Radiation Chemistry Studies with Heavy Ions, II [LaVerne]
J. LaVerne, R. Schuler, R. Steinbeck, University of Notre Dame

(26) Charged-Particle Gamma-Ray Coincidences as a Probe of Nuclear Structure at High Spin, II [Betts]
M. Hass, University of Rochester; H.-J. Körner, University of Munich; G.-E. Rathke, GSI; M. Drigert, INEL; K. Beard, University of Notre Dame; (R. R. Betts, T.-F. Wang, R. V. F. Janssens, T. L. Khoo, E. F. Moore, S. J. Sanders, F. L. H. Wolfs)

(27) Properties of Quasi-continuum States in a Rotor - (a) Gamma Strength Function; (b) Damping of Rotational Structure; (c) Lifetimes [Khoo]
M. Drigert, INEL; Z. Grabowski, Purdue University; K. Beard, D. Ye University of Notre Dame; (I. Ahmad, R. V .F. Janssens, T. L. Khoo, E. F. Moore)

(28) Further Development of a Radiocalcium Dating Method Using Accelerator Mass Spectrometry II [Paul]
M. Paul, Hebrew University; (P. J. Billquist, B. G. Glagola, W. Kutschera, R. C. Pardo, K. E. Rehm, J. L. Yntema)

(29) Evaporation Residue - Gamma-Ray Coincidence Measurements for $^{14}N+^{159}Tb$ [Kovar]
M. Vineyard, University of Richmond; C. F. Maguire, Vanderbilt University; (D. G. Kovar, R. V. F. Janssens, B. G. Glagola, D. J. Henderson, S. J. Sanders, B. D. Wilkins)

(30) Superdeformation Near A=190? [Janssens]
J. Cizewski, Rutgers University; M. Drigert, INEL; U. Garg, D. Ye, K. Beard, University of Notre Dame; Z. Grabowski, Purdue University; (I. Ahmad, R. V. F. Janssens, T. L. Khoo, F. Moore, F. L. H. Wolfs)

b. Outside Users of ATLAS and of ATLAS Technology During the Period January 1 - December 31, 1988

This list includes only those who were present at ATLAS for an experiment.

(1) University of Notre Dame
J. J. Kolata
U. Garg
A. Morsad
K. Beard
S. Dixit
R. Kryger
D. Ye
A. E. Livingston
A. Zacarias
Y. Lu
J. A. LaVerne
R. H. Schuler
R. T. Steinback

(2) Purdue University
P. J. Daly
Z. W. Grabowski
M. Quader

(3) University of Kansas
F. W. Prosser

(4) Texas A&M University
J. Natowitz
R. Schmitt
R. Wada
K. Hagel
Y. Lou
L. Cooke
H. Utsonomiya

(5) Hope College
P. Gonthier
D. Kortering
T. Koppenol

(6) University of Toledo
L. Curtis

(7) Laboratori Nazionali di Legnaro
G. Nebbia
G. Viesti
G. Prete
B. Fornal
R. Zanon
G. Nardelli

(8) EG&G Idaho
M. Drigert

(9) Hebrew University
M. Paul

(10) Rutgers University
J. Cizewski

(11) Vanderbilt University
C. Maguire
A. Ramayya
S. Zhu
J. Hamilton

(12) GSI
G. Rathke

(13) University of Rochester
M. Hass

(14) University of Birmingham
B. Fulton

(15) Oxford University
C. Pass

(16) Yale University
P. Parker
P. Magnes

(17) University of Richmond
M. Vineyard

(18) Technical University of Munich
H. Körner

(19) Max Planck Institute
D. Habs

(20) University of Jyvaskyla
W. Trzaska

(21) Daresbury
J. Lilley

(22) Naval Research Laboratory
W. Stapor
A. Campbell
A. Knudson
P. McDonald

(23) Florida State University
J. Fox
A. Frawley
E. Myers

(24) Kansas State University
T. Gray
K. Karnes
V. Needham

c. Summaries of the Continuing User Programs, January 1 - December 31,1988

c.1. The University of Notre Dame

(i) Nuclear Physics (U. Garg, M. Drigert*, K. Beard, S. Dixit, J. Kolata, R. Kryger, D. Ye, A. Morsad, J. Hinnefeld≠)

A group from the University of Notre Dame is playing an important role in developing the research program at ATLAS. One of their main interests is the study, in collaboration with ANL staff members, of the behavior of nuclei at high spin in the transitional region near ^{208}Pb (i.e. the Hg-Pt-Os nuclei), with emphasis on shape coexistence and configuration mixing. This group has also participated in most of the experiments performed with the recently completed BGO gamma-ray facility. A graduate student, Mr. D. Ye, is currently based at Argonne and performs his thesis work under the direct supervision of R.V.F. Janssens. Another project concerns the study of incomplete fusion, quasielastic reactions and the emission of light particles. In the past year studies of the ^{28}Si+^{208}Pb system were continued at higher bombarding energies. A major activity of this past year was the continued maintenance and development of the gamma-ray facility consisting of a BGO sum-multiplicity array of 50 elements combined with 12 Compton-suppressed germanium detectors. In this project, the Notre Dame group is responsible for the array. This task consists of assembling and testing the BGO detectors and developing the electronic read-out system.

*Now at EG&G Idaho, Inc., Idaho Falls
≠Now at KVI Groningen, The Netherlands

(ii) Atomic Physics (A. E. Livingston, A. D. Zacarias, Y. N. Lu)

In a collaboration with the Atomic Physics group of Argonne, measurements are being made of the fine structure in lithium-like and helium-like ions using beam-foil spectroscopy. The recent effort has been devoted to extending the measurements of the 2s-2p (J=2) transition in helium-like titanium to helium-like nickel and bromine ions. Precise measurements of 2s-2p transition energies in simple (few-electron) atomic systems provide stringent tests of several classes of current atomic-structure calculations. In the past year measurement of the $1s2s^3s_1$ - $1s2p^3p_2$ transition energy in helium-like nickel ($^{58}Ni^{26+}$) has been completed. A preliminary analysis yields a value of 226.210.06 Å in agreement with the theoretical value of 226.210.04 Å. This is the most precise measurement of a high-Z 2s-2p transition energy. The group is also participating in a measurement of the lifetimes of the 2^1S_0 state in helium-like nickel. This state is forbidden to decay to the ground state by emission of two E1 photons. The decay radiation forms a continuum out to the transition energy of about 8 keV. The radiation is detected with a Si(Li) detector. The excited state is formed in a thin carbon foil which is moved relative to the detector by means of a precision translator. The decay rate is measured as a function of foil-detector distance to determine the lifetime. The first run of this experiment was completed in the past year.

(iii) Radiation Chemistry (R. Schuler, J. LaVerne and R. Steinback)

In the last year, the Radiation Chemistry group has continued studies of the process of track formation, local density of radicals and other reactive intermediates formed in a heavy-ion track in water. The understanding of these processes is important because of increased usage of heavy ions in radiation biology and medical therapy. This program is an extension to higher energies of work begun at Notre Dame and ATLAS. In the last year experiments were performed using ^{11}B and ^{58}Ni projectiles at ATLAS energies to complete the original measurements. These experiments were extended to the full ATLAS energy for ^{11}B and a new set of experiments using a Fricke dosimeter.

c.2. Purdue University (P. Daly, Z. Grabowski, M. Quader, and W. Trzaska)

The Purdue University group is working on high-spin nuclear states at ATLAS, with several thesis students. They use in-beam gamma-ray techniques directed at several aspects of nuclear structure at high spin, testing the validity of the Z=64 sub-shell closure through spectroscopic studies of N=82 nuclei close to the proton drip line. They have extended these studies in the last year by making use of the Compton-suppressed germanium detectors of the BGO facility. The group has also built a superconducting solenoid lens that is used as a conversion-electron spectrometer. The group has provided assistance to other users of this device. An experiment on excited 0^+ states in ^{182}Hg was performed and is described elsewhere in this report.

c.3. University of Kansas and Vanderbilt University Collaboration (C. F. Maguire, A. V. Ramayya, F. W. Prosser, and V. Reinert)

Work has continued on the development of NaI(Tl) detectors for charged particles utilizing pulse-shape discrimination and time-of-flight for mass (A<6) and Z identification. The calibration procedure has been established and the detectors (presently 15) have been used in several experiments. Among these were measurements of light particles in coincidence with evaporation residues produced in the reactions $^{16}O+^{40}Ca$, $^{32}S+^{24}Mg$, and $^{12}C+^{197}Au$. Effort has been spent in the analysis of results obtained in studies of complete and incomplete fusion reaction processes in light heavy-ion induced reactions ($A_{proj} + A_{targ} < 60$). Model-simulation calculations (using PACE and LILITA) have been performed to test the sensitivity of evaporation residue velocity spectra and light particle energy and angular distributions to contributions of incomplete fusion processes. The focus of the analyses have increasingly turned to the coincidence data in which the NaI(Tl) detectors have been employed.

The group also undertook the study of the pulse height defect in silicon detectors. Different thicknesses of silicon surface barrier detectors as well as a lithium drifted silicon detector and a silicon strip detector were studied with beams of ^{11}B, ^{16}O, ^{29}Si, ^{58}Ni and ^{76}Ge ranging in energies from approximately 0.5 - 10 MeV/nucleon. The data was intended to extend previous measurements to higher energies and is in the process of being analyzed.

c.4. National Bureau of Standards (R. D. Deslattes, P. Indelicato, and E. Kessler, Jr.)

A program to carry out accurate spectroscopic measurements of X-ray transitions in hydrogen-like and helium-like titanium has been initiated in the past year. These measurements will provide important tests of QED and relativistic quantum mechanics. In order to produce clean spectral lines in the experiment, a gas target will be used to obtain the excited helium-like or hydrogen-like ions. In order to get reasonable cross sections for electron pickup, the technique of accel/decel will be employed, whereby beams of one- electron ions are obtained by stripping after the booster and then slowing down in the ATLAS section. In the past year, two runs have been carried out to develop the accel/decel technique. Beams of Ca^{q+} (q=18, 19 and 20) were accelerated to 205 MeV and then decelerated to 105 and 129 MeV. The beams were delivered to a gas target where various thicknesses of He, Ne, and Ar gases were used. A Si(Li) detector viewing the target monitored X-rays emitted at 90° to the beam axis. These test runs demonstrated the capability of ATLAS for producing the decelerated beams needed for the measurement of the 2p→1s transitions in helium-like titanium. This will require the installation of a crystal spectrometer on the atomic physics beam line at ATLAS.

c.5. University of Toledo (L. Curtis, and R. Schectman)

A series of measurements is in progress to study the level structures of high-Z Ne-like and Na-like ions. In 1986, a beam of excited Ne-like Ni^{18+} ions was produced in ion-atom collisions with a gas target and used to study LMM Auger emission. In the experiment, the Auger electrons ejected from the excited projectile ions were analyzed by an electron spectrometer at zero degrees with sufficient resolution to resolve individual Auger lines. The experiment is a test of fundamental atomic structure theory and of models regarding the dynamic excitation processes in highly-ionized multi-electron systems. In the past year the group, in collaboration with the Atomic Physics group at Argonne, participated in a measurement of the lifetime of the 2^1S_0 state in helium-like nickel. This measurement is an important test of relativistic quantum mechanics. An experiment is being planned to study the spectroscopy of Auger and Rydberg electrons from selectively-excited Ni^{q+} (q=16,17,18) ions. This work will be done in collaboration with groups from Western Michigan University and the Hahn-Meitner Institute.

c.6. Texas A&M University, Padova and LNL Collaboration (J. Natowitz, R. Schmitt, R. Wada, K. Hagel, Y. Lou, L. Cooke, H. Utsonomiya, G. Nebbia, G. Viesti, G. Prete, G. Nardelli, R. Zanon, B. Fornal)

This collaboration undertook measurements to determine the excitation energy dependence of the nuclear level density at excitation energies from 100 to 400 MeV by deriving the emission temperatures of neutrons, protons and alpha particles evaporated from compound nuclei produced in the reactions of ^{60}Ni with ^{100}Mo. Beam energies of 350 and 650 MeV ^{60}Ni were used. A pair of electrostatic deflectors were used to separate the evaporation residues from the beam. The residues were detected in two silicon strip detectors. The measurements consisted of a coincidence between the evaporation residues and other reaction products including neutrons, protons and alpha particles. The remainder of the detector system included four liquid scintillator neutron counters, two charged-particle telescopes and six light particle telescopes. Angular distributions of the emitted particles were measured with emphasis on the particles emitted backwards in the center of mass. The first analysis of the data has been published and presented at conferences.

d. ATLAS-Technology Transfer

In addition to providing assistance to outside users of the ATLAS beam, we are also providing assistance in the use of the ATLAS technology.

d.1. Florida State University (J. Fox, A. Frawley, and E. Myers)

Argonne has fabricated the niobium resonators and some auxiliary devices required for the superconducting-linac energy booster being built at Florida State University. Under this arrangement, personnel from FSU have come to ANL to assemble and test the resonators. The main resonator-fabrication work for FSU was completed during 1986, but several resonators were repaired and tested at Argonne during 1987.

d.2. Kansas State University (T. Gray, K. Karnes, and V. Needham)

Argonne is fabricating the niobium resonators and some other linac components required for the superconducting decelerating linac being built at Kansas State University. Several staff members from KSU spent a substantial period of time at ANL during FY 1985 in order to learn the technology, and they have continued to return during FY 1986 and FY 1987 in order to assemble and test the resonators. In the future, most of the KSU resonators will be tested at KSU in their own beam-line cryostats.

D. SUPERCONDUCTING LINAC DEVELOPMENT

(L. M. Bollinger, P. J. Billquist, J. M. Bogaty, B. E. Clifft,*
P. K. Den Hartog, P. Markovich, F. H. Munson, Jr., J. M. Nixon,** R. C. Pardo,
K. W. Shepard, I. R. Tilbrook, and G. P. Zinkann)

ATLAS is an accelerator system that has repeatedly broken new ground in accelerator technology ever since its beginnings in the mid 1970's. These developments have had a major impact on other low-energy heavy-ion accelerators, and the demonstrated success of ATLAS has given credibility to the planned use of RF superconductivity in several large electron accelerators.

In view of the pioneering nature of the work at ATLAS, there are continuing needs to upgrade the existing technology and continuing opportunities to develop new approaches. In order to satisfy these needs and exploit the opportunities, this activity is expected to extend well into the 1990's. This developmental effort is essential for the research-effectiveness of the ATLAS facility.

a. Plans for the Positive-Ion Injector

(L. M. Bollinger, P. K. Den Hartog, R. C. Pardo, and K. W. Shepard)

During 1988 and 1989, the primary activity in this program has been the development and construction of a positive-ion injector (PII) that will be capable of providing intense, high-quality beams of ions from the full periodic table for acceleration by ATLAS. The project is progressing much as was projected in last year's report, and we still expect the new injector system to be completed by late 1990.

The objective of the work is to replace the present ATLAS injector, a 9-MV tandem electrostatic accelerator and its negative-ion source, with a positive-ion source and a new form of superconducting injector linac. This approach is expected to increase the beam intensity by two orders of magnitude for all ions and to enable ATLAS to accelerate uranium beams of good quality and intensity. We believe that this uranium upgrade will give ATLAS unique capabilities for nuclear research with heavy projectiles having energies in the neighborhood of the Coulomb barrier.

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*Chemistry Division
**Engineering Physics Division

A schematic representation of the new injector system is given in Fig. II-3. The ion source for PII is an electron-cyclotron-resonance (ECR) source on a 350-kV voltage platform. Both mass analysis and a first stage of bunching are carried out on the voltage platform. A second-stage buncher and also second-stage mass analysis are carried out at ground potential. The source, first tested in late 1987, is the first ECR source operated at high potential.

The injector linac being built to accelerate the low-velocity ions from the ECR source consists of an array of four different kinds of independently-phased superconducting accelerating structures, all having 4 accelerating gaps formed by 3 drift tubes. These four classes of units are sized to be optimum for projectiles with relative velocities β of 0.009, 0.015, 0.025, and 0.038. The first three of these types operate at 48.5 MHz and the last type operates at 3/2 x 48.5 = 72.75 MHz. In total, the injector linac will have 18 resonators.

Construction of PII is being carried out in three phases. In Phase I, the goal is to build a small but useful prototype system consisting of a 3-MV linac and the ECR source on its voltage platform. The linac has just 5 resonators, all but one of which were built as prototype units. The overall length of the linac is only 10 ft. Because of the high charge state and the large beam currents of ions from the ECR source, even this tiny system will be competitive with the present FN-model tandem as an injector for many ions with $A > 40$ and will be superior for ions such as calcium that are difficult to make with a negative-ion source. Phase I was completed in early 1989 and is being put into service for research. Thus, the new technology will be well tested before the Phase III linac is completed.

Because of its limited accelerating power, the Phase I linac will be useful only for ions in the lower half of the periodic table. In Phase II, the addition of seven more resonators will extend the upper mass limit to at least $A = 190$. The availability of energetic ions in the upper half of the periodic table will greatly strengthen most of the experimental program by making it feasible to use inverse reactions (heavy projectiles on light targets).

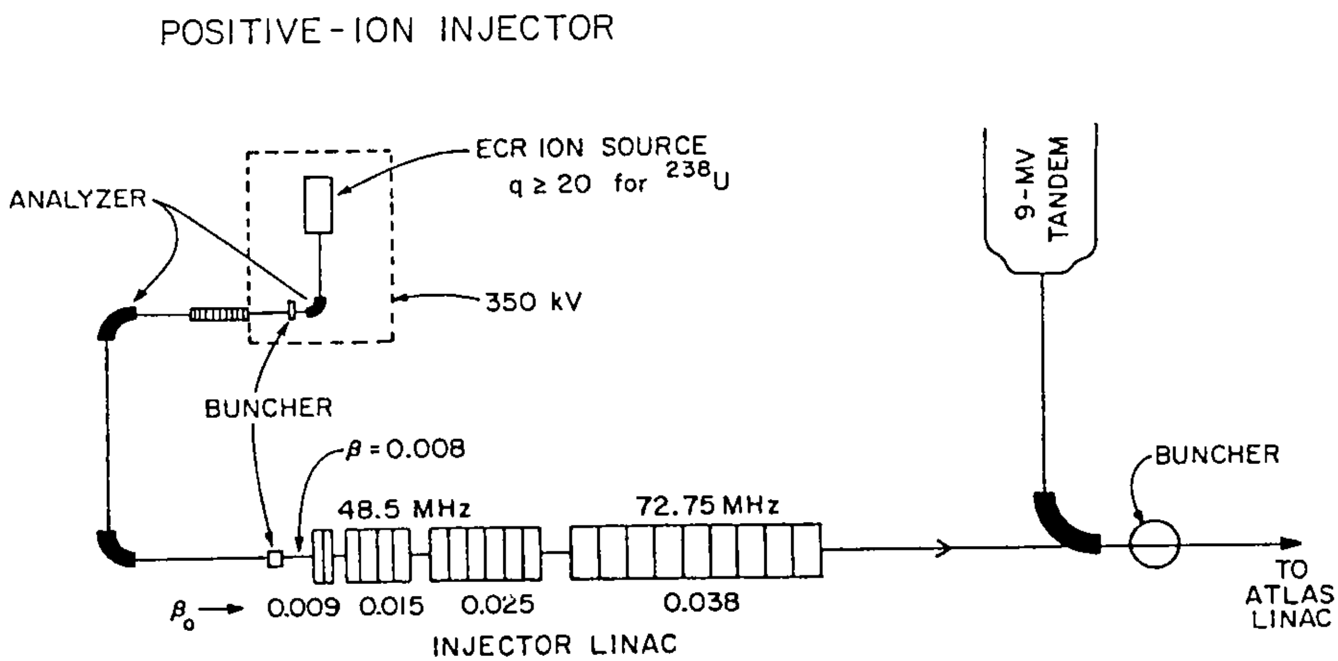

Fig. II-3. Schematic representation of the positive-ion injector. Magnetic quadrupole lenses in the beam line and superconducting solenoid lenses in the injector linac are not shown.

In Phase III, the objective is to enlarge the linac enough so that uranium ions can be accelerated up to the velocity required for efficient acceleration by the present ATLAS linac. This will be done by adding six more resonators, with the goal of completing the work by late 1990. The resulting 12-MV injector will enable ATLAS to provide intense high-quality uranium beams up to energies of about 8 MeV/A. In view of the good beam quality, high intensity, easy energy variability, and continuous (CW) character of these beams, ATLAS will be the ideal machine for the study of nuclear phenomena involving very heavy projectiles near the Coulomb barrier.

A primary requirement for PII is to provide output beams with quality that is as good or better than that for beams from the present tandem injector. Realistic ray-tracing calculations have shown that this requirement can be met. An important advantage for the injector linac is that it does not suffer the beam-quality deterioration associated with the stripping foil in the tandem terminal.

During 1988 and early 1989, work on PII has proceeded on a broad front, including refinement of the ECR source and its voltage platform, resonator fabrication and testing, cryostat fabrication and assembly, improvements in phase-control technology, fabrication of electronic control circuits, design and fabrication of bunching equipment, design and procurement of beam-line and linac-control systems, and building modifications. Additional information about some of these topics is outlined below.

b. Ion-source System (R. C. Pardo and P. J. Billquist)

The electron-cyclotron-resonance (ECR) ion source and its voltage platform have been completed in all essentials, and in late 1987 the source was operated for the first time. Since then, various technical problems have been solved and performance of the source has been steadily improved. Also, when not involved in developmental activities, it has been used for atomic-physics experiments.

1. ECR Ion Source

The main design features of the ECR source have been described in previous reports and will not be repeated here. Our goal was to build a source that can operate on a voltage platform and still compare favorably with existing general-purpose ECR sources with respect to charge-state distribution and beam current. The results obtained to date indicate that this primary objective has been achieved.

Examples of source performance when delivering beams from gases are shown in the following table, where beam currents are in electrical micro-amp. These results were obtained by mixing the gas of interest with either oxygen or helium as the support gas. Total RF power never exceeded 850 watts for operation. For the data in this table, the consumption of gas varied from a low of 1.2 mg/hr for krypton to 9 mg/hr for one operating mode with argon. All feed materials had normal isotopic composition, and the abundance of the isotope of interest is indicated at the top of the table. Beam currents are in electrical μA.

Q	100% ^{16}O	91% ^{20}Ne	92% ^{28}Si	99% ^{40}Ar	57% ^{84}Kr	26% ^{129}Xe
4	-	23				
5	70	-	15			
6	60	31	15			
7	5	20	15	40		
8	-	11	10	60		
9		0.4	5	30		
10			-	-		
11			.8	2.5	10	
12				1	-	
13					12	
14					-	5
15					8	4
16					-	-
17					4	2.5
18					-	1.5
19					2	-
20					0.8	1.0
21					-	0.4
22					-	-
23					0.2	0.3
24						-
25						0.2
26						0.2

In the course of bringing the ECR source into operation, numerous technical problems have been encountered and solved, in some cases by the redesign of parts of the apparatus. These difficulties include the failure of several components in the RF power system, voltage breakdown in the extraction system, and repeated failures of turbo-molecular pumps in the vacuum system.

An important requirement for our ECR source is that it must be able to provide intense high-charge-state beams for nearly all ions, especially materials that are normally solids. Consequently, the plasma chamber has been provided with convenient access. Now that the basic ECR source is functioning well for gases, a major activity since mid 1988 has been to develop techniques for using solid feed materials.

Three different techniques for vaporizing solid source material are being explored: (a) a metal wire inserted into the surface of the plasma, (b) an oven heated by an electric current, and (c) a tantalum crucible heated by the plasma. The suitability of each method depends, of course, on the bulk physical characteristics of the feed material. Examples of beam currents obtained with these techniques are shown in the table below. The result for ^{40}Ca is especially interesting since it demonstrates that it is easy to produce good calcium beams suitable for injection into the ATLAS linac, whereas the calcium beam from our tandem is too weak for many experiments. The consumption rate of calcium was 1.2 mg/hr for the data in the table. However, in the other tests the consumption rate was > 0.1 mg/hr. Again, the abundance of the isotope of interest is indicated above each column and beam currents are in the electrical μA.

Heating Technique for Solids

Q	Crucible 97% ^{40}Ca	Wire 68% ^{58}Ni	Wire 69% ^{63}Cu	Oven 100% ^{133}Cs
7	10	30		12
8	15	30		14
9	30	20		15
10	-	10	2.5	10
11	35	4	3.3	10
12	18	0.5	-	10
13	5		1.2	10
14	2			10
15				10
16				6
17				6
18				5
20				3
21				2
22				1.3
23				0.7
24				.25
25				.15
30				.025

While the ECR source is still in a developmental stage it is being used on a part-time basis for atomic-physics experiments. This usage has proved to be beneficial since it provides realistic long-term burn-in tests for both the source and the voltage platform. The atomic-physics work has been largely discontinued during the first half of 1989 because of the need for the source system in tests of other components of PII.

2. High-Voltage Platform

The high-voltage platform on which the ECR source is located is designed to operate at 350 kV above ground potential. Power is transmitted up to the platform by means of isolation transformers, and the resulting heat (more than 75 kW for the present source) is removed by means of low-conductivity flowing water.

The voltage platform successfully operated up to its design voltage (350 kV) on the first attempt and for many weeks thereafter. Tests at 100 kV showed that the ripple of the platform voltage is less than 1 volt. This remarkable stability suggested that high-voltage ripple may not have much impact on beam quality and that it will be feasible to form very narrow pulses for injection into the injector linac.

In spite of the good experience initially, voltage breakdown of the isolation transformers caused considerable delay in the development and use of the ECR source system during 1988. These commercial units are designed to provide 140 kW of power at 350 kV. We have experienced two rounds of failure, the first attributed by the manufacturer to poor workmanship and the second to a design error. Following the final assembly of the rebuilt transforms, the units were successfully tested by the manufacturer at 375 kV. However, in view of our experience, the operating voltage of the ECR voltage platform is being limited to 250 kV until after the Phase I system has been thoroughly tested. This limitation will not have much negative impact on the operation of the Phase I injector.

c. Injector Linac

1. Superconducting Accelerating Structures for Low-Velocity Ions
(K. W. Shepard, P. Markovich, G. P. Zinkann)

Prototypes of all four types of new superconducting resonators required for the injector linac have been completed and fully tested. All four types operate at accelerating fields above our original assumptions.

The performance of the prototypes at 4.2K are summarized by the following table:

	β=0.009	β=0.015	β=0.025	β=0.038
RF Frequency (MHz)	48.5	48.5	48.5	72.75
Assumed Operating Field (MV/m)	4.5	3.0	3.0	3.0
Measured Accel. Field (MV/m) for 4 W into Helium	6.2	4.6	3.9	4.2

From the above table one sees that the resonators for PII appear to be capable of operating at higher accelerating fields than was assumed initially and than is required to meet our design goals. Nevertheless, in view of experience here and elsewhere, it seems wise to continue to use the original assumptions to project accelerator performance until long-time on-line operating experience indicates that higher accelerating fields are realistic.

All four of the prototype units and one additional β=0.025 unit will be used in Phase I of PII. These resonators have all been completed and tested. The second β=0.025 unit also operated at 3.9 MV/m with 4 watts of RF input.

Six of the seven additional resonators required for Phase II of PII are being fabricated, and the niobium required for the six additional resonators of Phase III of PII has been ordered.

2. PII Linac Cryostat
(K. W. Shepard, P. Markovich, and G. P. Zinkann)

Because of the very different resonator geometry, virtually all elements of the PII linac cryostat are different than the existing ATLAS cryostats. Also, some subsystem designs have been upgraded: e.g., a new resonator mechanical support system, which should accommodate the more stringent mechanical alignment tolerances of the PII linac, and a greatly simplified liquid-nitrogen distribution system. The initial, prototype PII linac cryostat module has been fabricated and assembled, largely de-bugged, and successfully cooled down on several occasions.

3. Fast-Tuner System
(J. Bogaty, B. E. Clifft,* K. W. Shepard, and G. P. Zinkann)

The development of an improved fast-tuner system has been completed. Like the original fast tuner for ATLAS, the new tuner consists of a voltage-controlled reactance (VCX) switched between two states by a pulser-driver. The VCX is mounted directly on the resonators and is cooled by liquid nitrogen. The pulser-driver operates at room temperature. Both parts of the system make use of new components and are entirely re-designed. As a result, the tuning power of the device has been increased by a factor of four, and is now equivalent in tuning range to a 20-kW RF amplifier.

*Chemistry Divison

4. Injector Linac Electronics
(B. E. Clifft,* J. R. Delayen, B. G. Nardi, and K. W. Shepard)

The RF, cryogenic, and vacuum-control systems for the injector linac are based on the concepts used in the present accelerator, but most designs have been improved considerably. In particular, the resonator control module, used to stabilize the resonator amplitude and frequency, has been extensively redesigned to improve resonator diagnostics ability, to allow low-level mutlipacting barrier conditioning with the module, and to improve stability. These modules have performed extremely well, and the changes will be incorporated into the ATLAS control modules when funds are available.

*Chemistry Divison

New cryostat vacuum controllers have been designed using Programmable Array Logic (PAL's) chips. This electronics technology allows significantly reduced component count and circuit-board interconnections, with a concurrent increase in reliability and decrease in construction cost.

A liquid-nitrogen controller has been designed, based on a single-board computer and a new type of level sensor, in order to regulate more closely the supply of cryogen to the cryostat heat shields and VCX's. When applied to all of the cryostats, this controller should result in significant reductions in liquid nitrogen consumption.

5. RF Phase Reference System (B. E. Clifft,* J. R. Delayen, P. K. Den Hartog, F. H. Munson, Jr., and K. W. Shepard)

The RF phase reference system for PII was designed and constructed in a way that has been thoroughly tested during the past year in timing experiments at ATLAS. As was mentioned in last year's report, we have for several years experienced apparently random, infrequent changes of rf phase for one or more linac resonators, which necessitated time-consuming re-tuning of the machine. In the past year, the phase-control system has been upgraded by redesigning and replacing the distribution system for the signals from the RF master-clock oscillator. The upgrade has been in service for several months and has entirely eliminated the phase-jump problem. This great improvement in the long-term stability of the linac will significantly reduce the total time required for tuning by permitting previously-established tunes to be used with confidence.

*Chemistry Division

d. Helium Refrigeration System (L. M. Bollinger and J. M. Nixon*)

The injector linac will be cooled by flowing liquid helium that maintains liquid helium in a manifold in each cryostat, and liquid from these manifolds reach the resonators by gravity flow. The source of helium is a refrigerator that can either be dedicated to cooling the injector or can simultaneously be linked to the two existing refrigerators that cool ATLAS. This additional cooling for the existing ATLAS linac has significantly increased operational reliability.

A 100-watt refrigerator that is suitable for use with the Phase I injector has been installed, and the problems associated with the operation of this refrigerator in parallel with the two existing units have been solved. During April 1989, the 100-W refrigerator will be replaced by a 300-W unit on loan from another program.

*Engineering Physics Division

e. Control System of PII (P. K. Den Hartog, F. H. Munson, Jr., and I. Tilbrook)

In order not to interrupt the ongoing operation of ATLAS during the two-year period while the three phases of PII are being tested, all parts of PII are being controlled by an independent control system. This system consists of a separate PDP/11S[nn] computer and CAMAC highway interfaced to a dedicated control console with CRT and alphanumeric displays, assignable knobs, and beam diagnostic monitors. All of the functions of the ATLAS control console are reproduced for PII, but in a somewhat modified and improved form. The system was designed to make integration into the ATLAS controls as straightforward as possible after the PII has become the single injector to ATLAS.

A commercially available process control application program (THE FIX[nn]), operating on an MSDOS[nn] compatible computer with a Computer Products[nn] data-acquisition interface, is being used for accelerator cryogenic monitoring. The program allows rapid display generation and database configuration with extensive alarming and historical trending capabilities. This system will soon be connected via ethernet to the ECR control microcomputer and to other cryogenic monitoring nodes to form a local area network. We anticipate that we will increasingly rely on the rapidly expanding base of commercial applications and microcomputer hardware to solve accelerator control problems.

f. Beam Transport and Analysis System (P. K. Den Hartog and R. C. Pardo)

The beam-transport system linking the ECR source to the injector and the injector to ATLAS has been installed. The injection beamline was designed to be able to handle beams with rigidities up to 0.35 Tesla-m.

The ECR source will frequently be used to provide beams of rare isotopes from natural material and, consequently, the mass resolution of the injection beamline must be sufficient to separate the ion species of interest from the other species with similar q/A. The resolution of the system results from two successive 90-degree magnets: one on the ECR high-voltage platform, and the first magnet of an isochronous 180-degree bend. Including the effects of the energy spread introduced by the harmonic buncher located on the HV platform, the system yields a combined q/A resolution of about 0.2%. Beam transmission through the system in initial tests has been excellent, with nearly 100% achievable with reasonable care. Charge exchange losses under normal conditions are less than 1% for medium and low mass ions. Transverse diagnostics along the injector beamline are completely conventional, relying on wire-scanner profile monitors, Faraday cups, and adjustable slits.

g. Beam-Bunching System (R. C. Pardo, J. M. Bogaty, L. M. Bollinger, B. E. Clifft,* and K. W. Shepard)

Beam bunching for the injector is done in two stages, with the first buncher (B1) located on the ECR high-voltage platform and the second buncher (B2) placed immediately in front of the first resonator cryostat. A parallel-plate chopper is placed upstream of the second-stage buncher to remove tails. B1 is a gridded, harmonic, 12-MHz buncher similar in most respects to the pre-tandem buncher that has been used at ATLAS for a number of years. It differs only in the use of four harmonics rather than three in order to optimize waveform linearity. B2 forms the final time focus at the first resonator of the PII. It is a 24-MHz, room-temperature, spiral-loaded, 2-gap structure. The doubly-isochronous beam-transport system between the source and injector linac eliminates the variations in the path length of ion trajectories that would otherwise add significantly to beam-pulse widths. Pulse widths < 150 ps (FWHM) have been measured at the entrance to the injector linac.

Measurements of energy and time distributions of beams from the high-voltage platform are relatively difficult because of the low energy and heavy mass of the projectiles. Silicon surface-barrier detectors are used to measure both energy and time spectra at ATLAS, but for the slow-moving ions associated with PII, the detector resolution is very poor. Consequently, all beam diagnostics in energy-time phase space has been done by measuring ion time-of-flight spectra with a fast detector in which incident ions strike a 10-μ tungsten wire and the resulting electrons are accelerated to a channel-plate detector (see Section I.F.k).

h. First Beam Acceleration Tests of PII (R. C. Pardo, P. K. Den Hartog, L. M. Bollinger, B. E. Clifft,* K. W. Shepard, and G. P. Zinkann)

On February 28, 1989, the Phase I Positive-Ion Injector for ATLAS was used for the first time to accelerate ions up to the velocity required for injection into ATLAS. A 1-μA, 1.95-MeV beam of $^{40}Ar_{12+}$ ions from the ECR source was accelerated to 33 MeV by the five superconducting resonators of the Phase I injector linac. This beam was then further accelerated to 173 MeV by the ATLAS linac and delivered through a refined collimator to a gamma-ray facility for a 6-hour test experiment. A γ-ray spectrum measured in this test is shown in Fig. II-4.

*Chemistry Division.

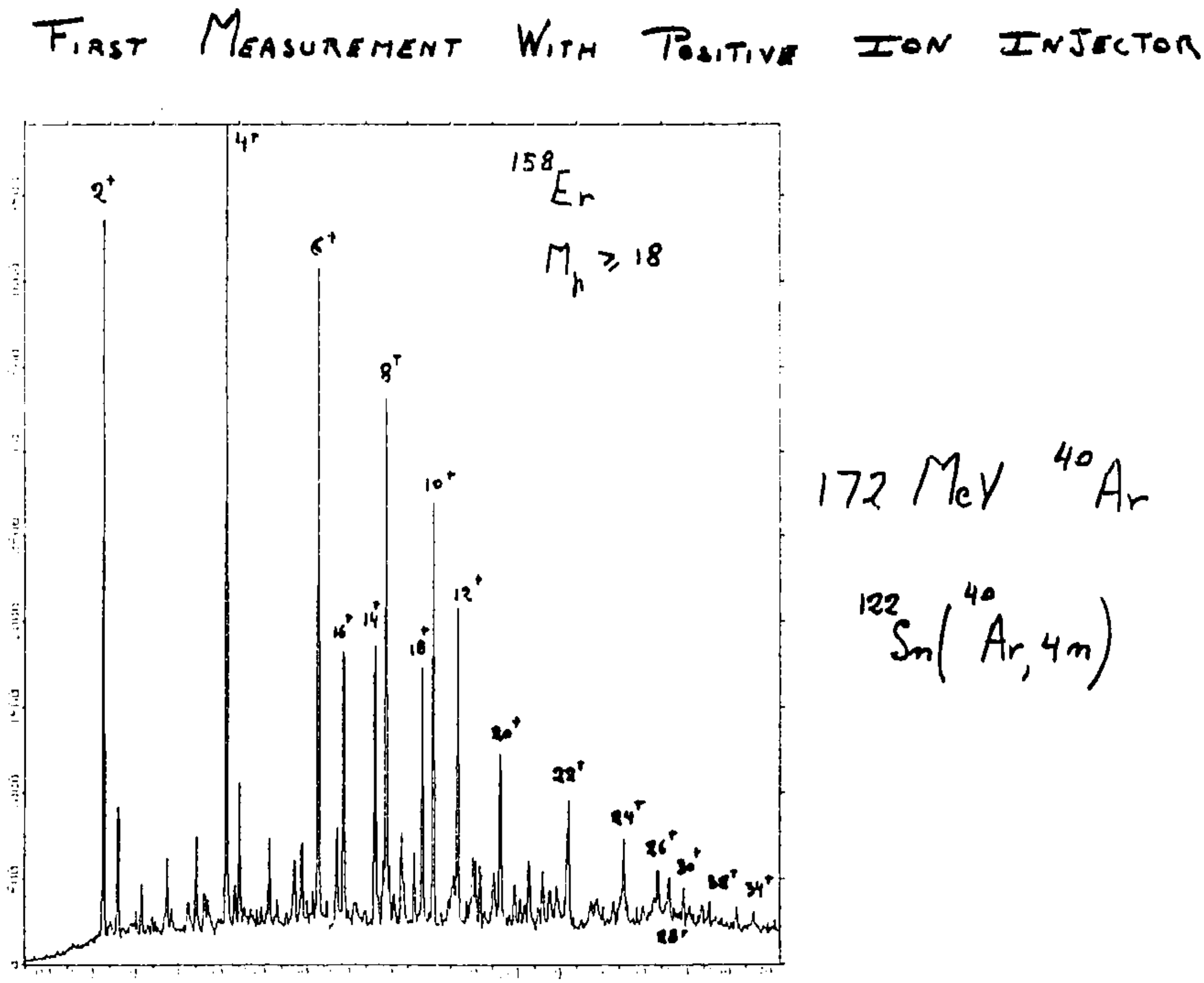

Fig. II-4. Gamma-ray spectrum measured by Robert Janssens and collaborators in first use of the positive-ion injector for physics research.

Below we summarize some performance results obtained in the initial acceleration test and in a following test in which a 2.44-MeV $^{40}Ar^{12+}$ beam from the source was accelerated to 36 MeV by the injector linac.

ECR Source. The ion source operated stably during the period of several days required for the test, as expected. The beam extracted from the source was originally 1 μA and was then reduced to about 200 nA in order to match the requirements of the planned measurement with the beam after acceleration through ATLAS.

Voltage Platform. The platform voltage was 150 kV and 190 kV in the two tests. Its ripple (peak to peak) was measured to be ~ 15 volts. A ripple of this magnitude has little effect on beam bunching.

q/A Analysis. The charge-to-mass ratio of the beam was analyzed in two stages: first on the voltage platform with a 90° magnet having a q/A resolution width of about 1.0% (FWHM) and then at ground potential with a large 90° magnet having a nominal resolution of 0.2%. Both magnets functioned well.

Beam Bunching. The 2-stage beam-bunching system for PII is similar to the one used successfully for many years at the present tandem injector: a harmonic buncher which operates on the source-extraction energy followed at higher energy by a buncher with a sinusoidal wave form. The important new feature for PII is that there is no stripping foil between the two bunchers, and consequently the phase ellipse can be manipulated with greater freedom.

The 1st-stage buncher was adjusted to form a waist in time of about 35 m downstream at ground potential, near the second-stage buncher. The measured pulse width was Δt = 1.2 ns (FWHM). The 2nd-stage buncher then rebunched the beam to a time waist 55 cm downstream, where the measured pulse width was Δt = 130 ps (FWMH). This time spread is remarkably small, since the beam energy was only 0.061 MeV/u; previously, for heavy ions, only beams from tandems (with energies > 1.0 MeV/u) had been bunched to less than ~ 1 ns.

Various pulse widths meausured with 1-stage and 2-stage bunching can be used to deduce the longitudinal emittance ϵ_Z of the beam entering the injector linac. The value derived is $\epsilon_Z \approx 4\ \pi$ keV-ns when the full beam is used (ϵ_Z is the area in energy-time phase space). Although this value is already very small, it can be reduced to $\epsilon_Z \approx 1\pi$ keV-ns by using the 2nd-stage analyzing magnet to limit the energy spread of the beam accepted for use. This procedure reduced beam intensity, of course, but it is sometimes useful because the ECR source provides more beam than is needed in many experiments.

The one problem experienced with the bunching system is that the 2nd-stage buncher is too far (~ 1.9 m) from the first resonator and consequently beam matching to the linac is poor in longitudinal phase space, i.e., the beam pulse is too wide at the first resonator. This is a temporary problem, since the injection geometry will be better for the final Phase III linac and since a better match can be obtained by using a higher injection voltage.

One has considerable flexibility in matching the beam to the linac by adjusting the pulse width incident on the 2nd buncher. The only limitation is that the incident pulse must be narrow enough to fall within the linear range of the 2nd buncher, say, within ± 2 ns.

Transverse Emittance. The measured transmission of the 2.44-MeV $^{40}Ar^{12+}$ beam through two widely spaced apertures indicates that $\epsilon_x \approx \epsilon_y \approx 12\ \pi$ mm-mrad. This is about what was expected.

Injector Linac. The 3-MV Phase-I injector linac consists of four types of independently-phased 4-gap accelerating structures [6] optimized for $\beta = 0.009$, $\beta = 0.015$, $\beta = 0.025$, and $\beta = 0.038$. The Phase-I system has one unit of each type except that there are two $\beta = 0.025$ units. A superconducting focussing solenoid follows each of the first three resonators.

The linac was operated stably, with all resonators under phase control, for about ten days. In spite of the low RF frequency, phase control was maintained easily. In the second run, the total accelerating voltage of the linac was ~ 3.5 MV (after correcting for transit-time effects), somewhat greater than the design value of ~ 3.1 MV.

The one disappointment was that the transmission through the linac was poor--about 30%. We are confident that this problem can be eliminated by reducing the following potential difficulties: (1) Earth's magnetic field. For the ion involved, this field was troublesome because our long injection beam line was unshielded. (2) Alignment of linac. The center line of the linac was probably misaligned relative to the incident beam. (3) Alignment of resonators. Several mechanical problems within the cryostat caused at least one individual unit to be misaligned. (4) Focussing elements. The transverse optics at the front end of the injector linac are complex, and the solenoid parameters used were far from optimum. (5) First resonator. The accelerating field of the first resonator was larger than required, thus causing unnecessary defocussing.

Quality of Accelerated Beam. A primary goal for the new injector is to achieve beam quality that is competitive with that of the tandem, especially in longitudinal phase space. Many doubted whether this could be done.

The longitudinal emittance of the beam out of PII can be determined reliably by measuring the widths of two time distributions: (1) the time spread at the rebuncher between PII and the booster linac and (2) the width of a time waist formed by the rebuncher. We obtain

$$\epsilon_Z = 5\pi \text{ keV-ns}.$$

This result is about 5 times smaller than the emittance of a tandem beam for ions in the same mass range, thus establishing a new standard of performance. Also, it is better than we had hoped for. Our measurements were not complete enough to determine to what extent the emittance is degraded by acceleration through PII, and we don't yet have any experimental data on how ϵ_Z depends on ion mass.

Conclusions. The results of the beam tests of the Phase I positive-ion injector indicate that all of our design goals for PII will be met. The good beam quality is especially gratifying since there are so many ways in which the beam from the source can be degraded.

i. Basic Technology of RF Superconductivity

a. RF Properties of High-Tc Superconductors
(J. R. Delayen,* C. Bohn,* M. T. Lanagan,** and K. W. Shepard)

Cylindrical rods of oxide superconductor have been used as the center conductor of a half-wave resonant coaxial line. In this apparatus, the superconducting rods are immersed in liquid nitrogen, which provides excellent cooling of the RF current-carrying superconducting surface. The rod samples of TBCO and bismuth-based high-Tc materials have been studied. RF surface magnetic fields of 650 gauss have been obtained with TBCO rods superconducting at 77k: this is by far the highest RF magnetic field observed in any high-Tc superconductor to date.

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b. Test of a Superconducting RF Quadrupole
(J. R. Delayen,* and K. W. Shepard)

To date, no superconducting RFQ structure has been built, although such structures might greatly increase efficiency and field strength, particularly for CW operation. Work has begun to temporarily modify the drift-tubes of an existing split-ring resonator to provide a strong RF quadrupole field. Tests of the modified cavity will provide a "sparking test", and will experimentally explore the practicability and desirability of developing superconducting RFQ accelerating structures.

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c. Cryogenic Calorimetric Detectors for Heavy Ions
(P. Egelhof,* K. W. Shepard, and W. Henning*)

In recent work, low-temperature calorimetric detectors have exhibited energy resolution of a few tens of keV for 5 MV alpha particles. The present project is to investigate the possibility of using such cryogenic detectors for high-resolution detection of heavy ions. For initial tests a germanium bolometer has been prepared and used at 2K to detect alpha particles. Work is in progress to optimize and test such detectors with heavy-ions in the energy range of a few MeV/u.

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III. MEDIUM-ENERGY NUCLEAR PHYSICS AND WEAK INTERACTIONS

In order to explore the internal structure of the nucleon and particularly those aspects which play a role in shaping the character of nuclear forces, the medium-energy research program in the Argonne Physics Division emphasizes the study of processes in nuclear matter in which interactions with the constituents of the nucleon describe the basic physics. Specific research topics include short-range properties of nuclear forces, nuclear pion fields, and quark degrees of freedom in the nuclear medium. Because energetic leptons provide an accurate well-understood probe of these phenomena, primary emphasis is placed on experiments involving electron- and deep-inelastic muon scattering. In Fermilab experiment E665, in which Argonne members play an essential role, deep-inelastic scattering of 500-GeV muons has been observed in coincidence with leading hadrons from a variety of nuclei. The very high muon energy and more detailed particle identification distinguish this measurement from previous experiments. The primary objectives of the collaboration are a study of the quark hadronization process and the mass dependence of the quark structure functions. The data from this experiment will address a central issue in nuclear physics, the modification of the structure of the nucleon in nuclear matter. The Argonne group is responsible for data-acquisition software management, for one of the gas Cerenkov particle-identification detector systems, and with several other collaborating institutions for the construction of a new vertex detector system.

Almost all of the technical resources of the medium-energy physics program are devoted to the development of a new target technology which will be used to study elastic electron-deuteron scattering to very high momentum transfer. The tensor polarization of the recoil deuteron in this kinematic region is very sensitive to sub-nucleonic effects in nuclei, most notably meson-exchange and quark effects. A collaboration between the Argonne group and a Soviet group of physicists at Novosibirsk has been formed to carry out such measurements. A polarized deuterium gas target intercepting the circulating beam of an electron storage ring will be employed and the interactions of the deuterium gas with the circulating electrons will be used to study polarization effects in elastic and inelastic scattering. Construction of a prototype target and demonstration of feasibility have already been completed. Current efforts are focussed on development of more advanced target designs which will allow extension of measurements to large momentum transfers. The experiment will be performed at Novosibirsk in two phases during the next two years at the 2.5-GeV VEPP-III electron storage ring. The program at Novosibirsk will also provide a proof-of-principle for a proposal to study the spin-structure of the nucleon using internal polarized hydrogen and deuterium targets at the HERA electron storage ring. The Argonne group has the primary responsibility for target cell design in preparing a broad US-European research proposal for installation of an internal target in the third interaction section of the HERA ring to pursue nucleon-structure studies.

Other important initiatives involve electron scattering experiments at the MIT-Bates Laboratory, at the Saclay Linear Accelerator (ALS), and preparations for experiments at CEBAF. The intent of the work at Bates is to provide a much better constraint on the nucleon mean-free path in nuclei by performing (e,e'p) coincidence measurements in the quasifree region for a variety of nuclei. The work at ALS is concerned with the study of charged-pion electroproduction in deuterium and ^3He in kinematics where the "virtual-pion photo-effect" is expected to dominate. The production cross section and pion energy spectrum are expected to reveal information on the pion field in nuclear matter. The medium-energy physics program has made a major commitment to participate in the research program at CEBAF. Staff members are actively involved in development of the designs of the experimental facilities, and in preparation of research proposals for measurements when beam becomes available. Members of the group expect to participate in the construction of one of the core spectrometers at CEBAF, and, if sufficient resources are provided, the group expects to assume responsibility for the construction of a broad-purpose short-orbit spectrometer to be made generally available to the users at CEBAF.

The second major area of concentration in the medium-energy physics program is the study of relativistic heavy-ion reactions with nuclei. Here the emphasis is on understanding reaction mechanisms and determining features of the nuclear equation of state at high energy density where qualitatively new phenomena have been predicted. The primary activity is participation in a major collaboration at the Brookhaven National Laboratory AGS, experiment E802. The objective of this series of measurements is establishment of the particle-production systematics in reactions induced by 15-GeV per nucleon ^{16}O and ^{32}Si ions on various nuclear targets. E802 is the initial phase of a program at the AGS to explore the properties of heavy-ion reactions at the highest energies and target/projectile masses possible with current and planned heavy-ion accelerator beams.

Weak interactions at low energy is the third major component of the medium-energy physics program. Much of our understanding of the fundamental weak interaction has come from low-energy experiments. The program in the Physics Division is involved in testing the "Standard Model" of unification of weak and electromagnetic forces as well as searching for phenomena that signal physics beyond our present understanding. The search for neutrino oscillations at LAMPF is a major activity of the Argonne group. The experiment (E645) is a collaboration with physicists from Caltech, Los Alamos, Ohio State University and Louisiana State University. The Argonne group has been responsible for the design, construction and operation of the active cosmic-ray shield for the neutrino detector used in E645. In an ancillary activity, the Argonne group is operating the shield in conjunction with a large-shower-detector array of the Cygnus group at Los Alamos to study high-energy cosmic-ray point sources. Measurements of free-neutron beta decay are carried out at the Institute Laue-Langevin in collaboration with scientists from the Institute and the University of Heidelberg. The objective of these studies is to provide the best determination of the weak-interaction coupling constants. Argonne scientists also study beta decay in light nuclei. A new measurement of the partial decay rate of ^{10}C will further constrain the vector-coupling constant which determines the Cabibbo angle. Measurements of the decay of polarized mirror nuclei such as ^{8}Li are planned as tests for the presence of induced currents and to provide new estimates of the strength of the vector-coupling constant. An increasing portion of this component of the program is devoted to the study of nuclear reactions on light nuclei at low energy which have important implications for astrophysics and cosmology.

A. SUBNUCLEON EFFECTS IN NUCLEI

Most noteworthy in FY 1988 was the completion of an experiment at the Nuclear Physics Facility at SLAC (NPAS) which provides strong evidence for the failure of conventional pion-exchange theories to explain the short-range properties of nuclear forces. In this experiment, two-body photo-disintegration of the deuteron was studied for photon energies above 1 GeV. The energy variation of the reaction was observed to approach the form expected from quark counting rules. A companion experiment at NPAS, a study of electroproduction of the delta in nuclei, was completed and published. Experiment E665, a study of deep-inelastic muon scattering, in progress at the new muon laboratory at Fermilab, received beam from June 1987 to February 1988. All of the elements of the detection system were brought into operation, and an extensive body of data was accumulated for targets of hydrogen, deuterium and xenon. These new data will provide valuable information on the A-dependence of hadron production and structure functions. Design work began on a new set of vertex chambers which will increase the integrated luminosities one will obtain in the next data run by more than an order of magnitude. Members of the medium-energy group joined with staff of the Institute for Nuclear Physics at Novosibirsk in a collaboration to measure the polarization effects in electron-deuteron interactions at the VEPP-III electron storage ring. Argonne is providing the storage cells and laser-driven polarized sources for the internal targets and the Novosibirsk group is responsible for detector and storage-ring operations. The program has already provided the first successful demonstration of storage cell operation with polarized atoms in a storage ring. Work continued on development of a high-density laser-driven polarized deuterium source to be used in the final phase of the experiment.

The first studies of electroproduction of pions in nuclei were completed with the successful measurement of the pion energy spectrum from deuterium. The experiment is a collaboration at the ALS-Saclay accelerator involving members of the Argonne and Saclay staffs. Data analysis was completed on a study of the nucleon mean-free path in nuclei, a quasifree electron-scattering experiment performed at the MIT-Bates Laboratory. In addition to the ongoing research, Argonne staff participated in the preparation of the conceptual designs for the experimental facilities planned at CEBAF. The Argonne group has proposed to assume responsibilities for construction of a short-orbit hadron spectrometer and the detector package for a 6-GeV core spectrometer. Staff members submitted seven letters of intent for experiments using first available GeV beams, scheduled for use in 1994.

a. Deep-Inelastic Muon Scattering from Nuclei with Hadron Detection

(D. Geesaman, R. Gilman, M. Green, H. Jackson, S. Kaufman, S. Tentindo-Repond, R. Kennedy,* H. Kobrak,* A. Salvarani,* Robert A. Swanson,* A. Eskreys,† P. Malecki,† K. Eskreys,† B. Pawlik,† J. F. Bartlett,‡ G. B. Coutrakon,‡ J. Hanlon,‡ T. Kirk,‡ H. Melanson,‡ H. E. Montgomery,‡ J. G. Morfin,‡ A. M. Osborne,‡ S. Wolbers,‡ T. Dreyer,§ M. Erdmann,§ J. Hass,§ W. Mohr,§ H. Stier,§ M. Wilhelm,§ J. M. Conrad,¶ D. G. Michael,¶ R. B. Nickerson,¶ F. M. Pipkin,¶ M. Schmitt,¶ Richard Wilson,¶ M. R. Adams,# C. Halliwell,# S. Magill,# D. McLeod,# L. Sexton,# S. Aid,** S. Kunori,** S. O'Day,** E. J. Ramberg,** A. Skuja,** P. H. Steinberg,** R. L. Talaga,** P. Anthony,†† M. D. Baker,†† W. Busza,†† T. Lyons,†† L. Osborne,†† J. Ryan,†† V. Eckardt,‡‡ H. J. Gebauer,‡‡ G. Jansco,‡‡ A. Manz,‡‡ S. Söldner-Rembold,‡‡ H. J. Seyerlein,‡‡ P. Stopa,‡‡ P. Strube,‡‡ H. J. Trost,‡‡ M. Vidal,‡‡ A. A. Bhatti,§§ T. Burnett,§§ R. Davisson,§§ W. Dougherty,§§ D. M. Jansen,§§ S. Krzywdzinski,§§ J. Lord,§§ H. J. Lubatti,§§ J. Wilkes,§§ T. Zhao,§§ H. Braun,¶¶ U. Ecker,¶¶ A. Röser,¶¶ S. K. Dhawan,## V. W. Hughes,## K. P. Schüler,## and H. Venkataramania##)

Deep-inelastic muon scattering from nuclei at CERN provided the first convincing evidence that the structure of nucleons is modified in the nuclear medium. This had profound implications on the understanding of nuclear dynamics. Many low-energy nuclear measurements had previously suggested interpretations involving modification of the nucleon structure. However, the muon-scattering data, which are sensitive to the incoherent scattering from the quarks in nuclei, can indicate the difference between the quark-distribution functions in the free nucleon and in nuclei. The conclusion of these studies was that the distribution of the fraction of the momentum carried by the quarks, F(x), is shifted to lower fractional momenta, x.

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Theoretical interpretations include a possible rescaling of the nucleon size in nuclear matter or the effect of an enhanced meson field in the nuclear interior.

A new experiment, E665, using the Tevatron II at Fermi National Accelerator Laboratory will provide new information on the nuclear effects on nucleon properties by studying deep-inelastic muon scattering with coincident hadron detection. The key features of this experiment are: 1) An open geometry allowing essentially 4π-hadron detection. 2) A streamer-chamber vertex detector for low-energy fragments. 3) Two large-field-volume superconducting magnets, with field strengths of 4 T-m and 7 T-m to provide accurate measurements of the muon and hadron momenta. 4) A particle-identification system including a ring-imaging Cerenkov counter which can separate pions, kaons and protons from 7.0 GeV/c to 150 GeV/c. 5) A muon beam energy of 500 GeV, a factor-of-two higher than was previously available. This high beam energy makes the experiment particularly suited to the study of the region of $x < 0.1$, where there is little or no data from other measurements.

A small-angle trigger has been added to the experiment to study deep-inelastic events at very low Q^2, down to 0.3 $(\text{GeV/c})^2$. This enhances the capabilities of the experiment at small x and in studies of shadowing phenomena.

The hadron detection provides several important new directions for this research. With the excellent particle identification, the flavor dependence of the fragmentation properties of nucleons in nuclei can be studied. This allows the isolation of features of the quark sea from the valence quark distributions. Furthermore, the time required for the struck quarks to form hadrons is sufficiently long that hadronization takes place both inside and outside the nucleus. This permits the study of the propagation of quarks through the nucleus and the effects of the nucleus on the hadronization process.

Argonne is responsible for two aspects of the experiment. The first is the management of the on-line data-acquisition software. An integrated system based on the FNAL VAXONLINE and RSXDA products controlled data acquisition from seven CAMAC branches and three FASTBUS segments involving three PDP-11/34 front-end computers, two VMS systems for data concatenation, logging and analysis, and several microprocessors for specific detector monitoring. In the 1987-1988 run, this system was capable of an instantaneous event rate of 70 events per second with each event averaging 10,000 bytes in length. The most serious issues involve the flow of data and control information between the various machines.

Argonne is also responsible for a gas-threshold Cerenkov counter, C1, which is required for particle identification in the 5-20-GeV region. This detector was in routine operation throughout the 1987-1988 run. Work has continued on integrated particle-identification strategies within the experiment.

E665 received beam from June 1987 to February 1988. All of the elements of the experiment were brought into operation with the exception of the level-two unbiased trigger. Data were accumulated with a beam-veto trigger at two energies: 500 GeV and 100 GeV on targets of liquid deuterium (luminosities of 2×10^{36} and 2×10^{35} muon-nucleon/cm^2 at the two energies, respectively) and gaseous xenon (7×10^{35} and 2×10^{35} muon-nucleon/cm^2 respectively). 500-GeV data were accumulated on a liquid-hydrogen target (7×10^{35} muon-nucleon/cm^2). These first data will already provide a comparison of the A dependence of hadron production with better statistics than the CERN measurements. They should also provide a valuable check on the structure functions for $0.05<x<1$ and new information at $x<0.05$.

Data analysis has been a major activity in 1988 and the first results of the entire analysis chain are beginning to become available. It is expected that the first physics results will be available in the middle of 1989.

During the next fixed-target run, the collaboration will concentrate on higher statistics comparisons of the nucleus dependence of the structure functions and hadron production. A new target mechanism is being designed to rapidly change targets (every minute) and a new set of vertex chambers is planned to replace the streamer chamber. It should be possible to obtain luminosities of 4×10^{36} muon-nucleon/cm^2 on each of five targets.

b. Electron-Deuteron Scattering With a Polarized Deuterium Gas Target in the VEPP-III Electron Storage Ring (R. J. Holt, R. Gilman, E. R. Kinney, R. Kowalczyk, J. Napolitano, L. Young, S. I. Mishnev,* D. M. Nikolenko,* S. G. Popov,* I. A. Rachek,* A. B. Temnykh,* D. K. Toporkov,* E. P. Tsentalovich,* D. K. Vesnovsky,* B. B. Wojtsekhowski,* V. G. Zelevinsky,*)

The most powerful method of isolating the charge and quadrupole form factor of the deuteron involves electron elastic scattering from a tensor-polarized gas target in an electron storage ring. The medium-energy group has embarked upon a collaborative effort with the Institute for Nuclear Physics at Novosibirsk for the purpose of measuring the tensor analyzing power in electron-deuteron elastic scattering at the VEPP-III electron storage ring. The basis for this collaboration is the Argonne group's expertise in laser-driven polarized sources and storage cells for gas targets, and the Novosibirsk group's experience with electron scattering from thin internal targets in electron rings. The experiment is expected to proceed in three stages: i) the use of a simple passive storage cell and a conventional atomic-beam source to obtain a target thickness of $\gtrsim 6\times10^{11}$ cm^{-2}; ii) an active high-density storage cell with a conventional source to increase the target thickness to approximately 6×10^{12} atoms/cm^2; and iii) a laser-driven source and the active storage cell to increase the thickness to $\gtrsim 1\times10^{14}$ atoms/cm^2.

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The first phase of this experiment was initiated last February when Argonne delivered a passive storage cell to Novosibirsk and assisted with its installation in the VEPP-III ring. The placement of the storage cell with respect to the atomic beam source and the VEPP-3 electron beam is shown schematically in Fig. III-1. The first systematic tests of the storage cell were conducted last summer and as a result we have provided the first successful demonstration of operation of a storage cell for polarized atoms in an electron ring. This passive storage cell was found to increase the target thickness over the polarized jet target by a factor of three and no loss in target polarization was observed. Presently, tensor-analyzing-power measurements in electron-deuteron scattering are in progress.

The high-density (phase II) storage cell is in the construction phase and is expected to be installed in the VEPP-III ring during the spring of 1989. Tests of the laser-driven polarized deuterium source are in progress at Argonne for the phase III target, and thus far a polarization of 30% has been achieved at a flow rate of 6×10^{16} atoms/s. Although this work represents the first demonstration of a polarized source based on spin-exchange optical pumping, the polarization and flow rate must be increased significantly during the next year in order to produce a practicable polarized target for phase III at Novosibirsk.

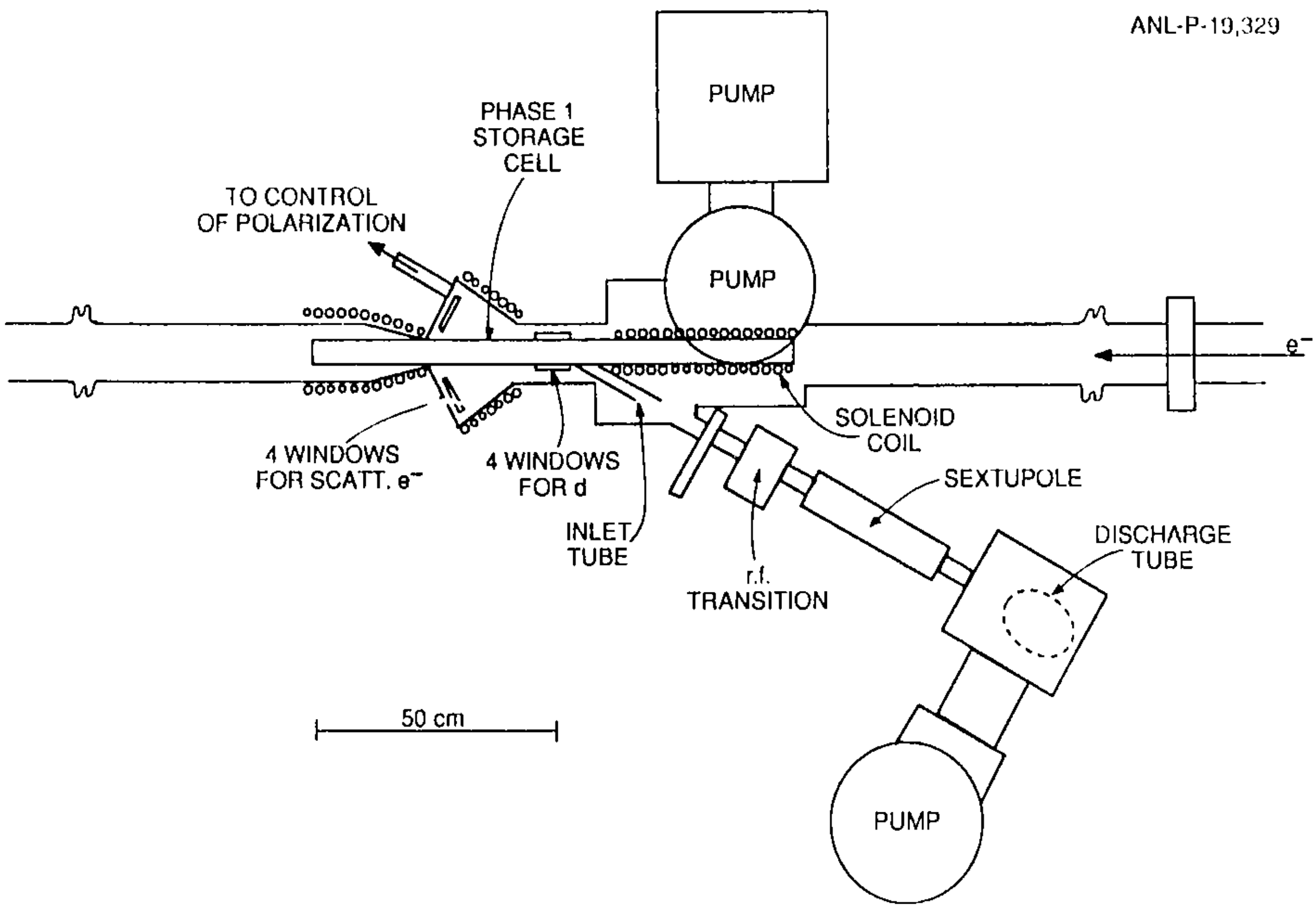

Fig. III-1. Schematic diagram of the storage cell in the VEPP-3 ring.

c. Two-body Photodisintegration of the Deuteron Above 1 GeV

(R. J. Holt, S. J. Freedman, D. F. Geesaman, R. Gilman, M. C. Green, H. E. Jackson, R. Kowalczyk, C. Marchand, J. Napolitano, J. Nelson, B. Zeidman, D. Beck,* G. Boyd,* D. Collins,* B. W. Filippone,* J. Jourdan,* R. D. McKeown,* R. Milner,* D. Potterveld,* R. Walker* C. Woodward,*, R. E. Segel,† T.-Y. Tung,† P. Bosted,‡ E. Kinney,§ Z.-E. Meziani,¶ R. Minehart#)

The differential cross section for two-body photodisintegration of the deuteron was measured for the first time above a photon energy of 1 GeV. The experiment was performed at the Nuclear-Physics-at-SLAC facility. An electron beam from SLAC was allowed to impinge on a Cu radiator. The bremsstrahlung photons from this process then irradiated a liquid deuterium target and the photoprotons from the $^{2}H(\gamma,p)n$ reaction were analyzed and detected with the 1.6-GeV spectrometer.

The results[1], represented by the darkened circles in Fig. III-2, for $\theta_{cm}=90°$ were found to be in disagreement with a recent[2] meson-exchange calculation (solid line) above 1.0 GeV. However, the energy dependence of the highest energy data are consistent with an s^{-11} dependence (s=total energy in the center of mass) as expected from the quark counting rules.[3] This result is apparent in the upper panel of Fig. III-2. This is the first result for a nuclear reaction that is found to be consistent with the constituent counting rules. Data taken at other reaction angles are presently undergoing analysis.

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[1]J. Napolitano et al., Phys. REv. Lett. 61, 2530 (1988).
[2]T.-S. H. Lee, Proc. of Int. Conf. on Medium and High-Energy Nuclear Physics, Taipei, Taiwan, 1988.
[3]S. J. Brodsky and G. R. Farrar, Phys. Rev. D 11, 1309 (1975).

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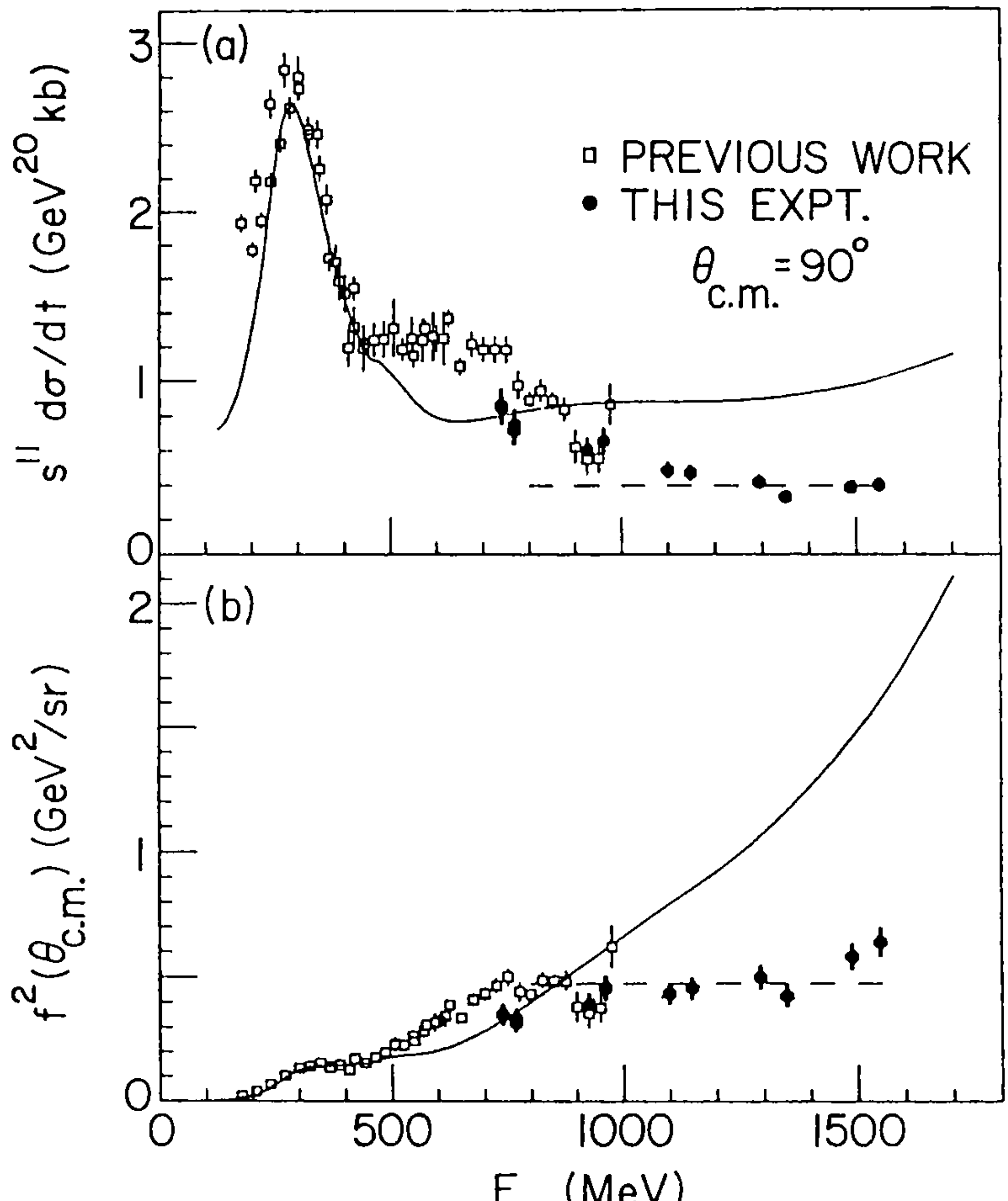

Fig. III-2. Results of our experiment at θ_{cm}=90° along with results of previous experiments at lower energies. The data are plotted so as to elucidate "scaling" as determined by (a) simple constituent counting (Ref. 3) and by (b) a formalism based on the reduced nuclear amplitudes (Ref. 4). The solid lines are the result of a recent calculation based on meson exchange (Ref. 2). The dashed lines represent constants that approximate the data at high energy but whose magnitudes are not predicted by any model. Only statistical errors and errors due to the uncertainty in the end-point energy are shown.

A reduced nucleus amplitude analysis has been applied to the $\gamma d \to pn$ reaction by Brodsky and Hiller.[4] This analysis is based upon the constituent counting, but a reduced amplitude $f(\theta_{cm})$, i.e. nucleon form factor dependence removed, is extracted and is expected to be independent of the photon energy when the analysis is valid.

The reduced amplitude was extracted from the present data and presented in the lower panel of Fig. III-2. Clearly, the agreemente of the data with the reduced amplitude analysis is not as good as that with the constituent counting rules alone. However, higher energy data are necessary before strong conclusions can be made with regard to the theoretical models.

It is absolutely imperative that these measurements be extended to high photon energy ($\gtrsim$3 GeV) as a more stringent test of the energy dependence of the cross section, since presently the s-range where the data are consistent with the quark model is relatively small (s=8.5-10 GeV^2). We have submitted both a proposal to NPAS and a Letter of Intent to CEBAF as the only two possible avenues available to extend these studies to higher energy.

[4]S. J. Brodsky and J. R. Hiller, Phys. Rev. C 28, 475 (1983).

d. Electroproduction of the Delta Isobar in Nuclei

(D. Baran,* D. Geesaman, M. Green, R. Holt, H. Jackson, B. Zeidman, P. Seidl, B. Filippone,† J. Jourdan,† R. McKeown,† R. Milner,† D. Potterveld,† R. Walker,† R. Segel,‡ and J. Morgenstern§)

Excitation of the $\Delta(3,3)$ resonance is the dominant feature of electromagnetic and hadronic interactions with nuclei in the region of energy-transfer between pion threshold and 500 MeV. In a recently completed experiment which is part of the Nuclear-Physics-at-SLAC (NPAS) program, high-energy (>1.5 GeV) measurements were extended to the medium-heavy nucleus, Fe, and for the first time a longitudinal-transverse decomposition of the inclusive cross section from pion threshold through the delta region was carried out for C and Fe targets at a four-momentum transfer of Q^2 = 0.1 (GeV)^2. Such a decomposition

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is vital to understanding the response of nuclear matter to large transfers of energy and momentum. The SLAC 1.6-GeV and 8-GeV spectrometers were used to observe the scattering of medium-energy (T = 0.5 to 2.0 GeV) electrons. The new data provided limits on the contributions to the integrated Coulomb sum rule of charge-dependent processes including the longitudinal tail of quasifree scattering in the Δ region. It has been suggested that the apparent quenching of quasifree charge scattering in heavy nuclei is due to the transfer of longitudinal strength to higher excitation because of correlations in nuclear wave functions. The residual longitudinal cross sections measured do not provide the additional strength needed above the quasifree region to satisfy the sum rule. The inclusive cross sections per nucleon for C and Fe are observed to be equal in the delta region. The transverse cross sections are in good agreement with data from photoabsorption. The failure of microscopic calculations to reproduce the transverse cross sections is striking and indicates the importance of mechanisms involving removal of more than two nucleons from the ground state. An accurate theoretical description of the transverse response incorporating modes involving meson-exchange currents and all Δ absorption channels will be vital to understanding this data. A paper describing the results has been published.

e. Pion Electroproduction in Deuterium (H. E. Jackson, R. Gilman, R. Holt, M. Bernheim,* G. Fournier,* A. Gerárd,* J. M. Laget,* A. Magnon,* C. Marchand,* J. Morgenstern,* J. Mougey,* J. Picard,* D. Reffay,* B. Saghai,* S. Turck-Chieze,* and P. Vernin*)

Pion electroproduction on nucleons bound in nuclear matter may be significantly different from production on free nucleons because of the contributions of higher-order processes involving neighboring nucleons. Such multinucleon processes are a basic feature of nuclear matter and their study can provide useful insights into the properties of nuclear forces. To explore the use of electroproduction as a probe of such processes we have begun a series of experiments at the Saclay electron linac (ALS) to study the reaction in simple nuclear systems. The first measurements, on charged-pion electroproduction in deuterium, have been completed and the results are under study. One of the principal objectives is a determination of the ratio of the differential cross section for production of positively-charged pions in

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the direction of the virtual photon from a proton bound in the deuteron to that of the free proton. Measurements have been made for invariant masses of the photon-nucleon system of 1160 MeV and 1232 MeV. Observations were made with the same cryogenic target and identical geometric conditions. At 1160 MeV, electroproduction on the proton is predominantly longitudinal for pion emission in the direction of the virtual photon and the pion pole term makes the largest contribution to the cross section. For the kinematics corresponding to W = 1232 MeV, the delta amplitude replaces the pion pole term as the dominant process. The energy of the incident electrons was 645 MeV. Charged pions are observed in the 600-MeV/c arm and electrons in the 900-MeV/c arm of the Saclay coincidence electron spectrometer system at ALS. The shape of the pion spectrum observed for the deuteron is well described by quasifree electroproduction on a proton bound in the deuteron. The ratio of the differential cross sections for the deuteron and proton was determined by integrating the spectra observed in missing mass. The ratio measured is significantly less than unity. For our kinematics, the virtual pion momentum probed in the charge-scattering process is about 200 MeV/c. The pion excess is predicted to be negative in this momentum range. Our preliminary result for the deuteron-to-proton ratio is consistent with this theoretical trend. Regardless of the specific interpretation of the value, it is clear that even in the lightly-bound deuteron, multi-body processes produce important modifications of the basic production amplitude.

f. Study of Pion Absorption in ^{3}He through the $(\pi^+,2p)$ and (π^-,pn) Reactions (D. F. Geesaman, J. P. Schiffer, B. Zeidman, D. Ashery,* G. S. F. Stephans,† B. D. Anderson,‡ R. Madey,‡ R. C. Minehart,§ S. Mukhapadhyay,¶ E. Piazetsky,# R. E. Segel,** C. Smith,§ and J. Watson,‡)

The analysis of experimental data from pion absorption at 165-, 250- and 500-MeV pion kinetic energies by ^{3}He is the subject of two Ph.D. theses by students at the University of Virginia and Northwestern University. Progress has been somewhat slower than might have been hoped, but the study should be completed in 1989.

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g. Proton Propagation in Nuclei and the A Dependence of the (e,e'p) Reaction in the Quasifree Region (D. F. Geesaman, R. A. Gilman, M. C. Green, R. J. Holt, J. P. Schiffer, B. Zeidman, G. Garino,* M. Saber,* R. E. Segel*, E. J. Beise,† G. Dodson,† S. Hoibroten,† L. D. Pham,† R. P. Redwine,† W. W. Sapp,† S. A. Wood,† C. F. Williamson,† N. S. Chant,‡ P. G. Roos,‡ J. D. Silk,§ M. W. Deady,¶ and X. K. Maruyama#)

Information on the propagation of nucleons in the nuclear medium is essential for tests of the nuclear many-body problem and for the analysis of many processes, including pion absorption and inclusive proton scattering. In many instances, proton scattering of a few degrees and energy loss of several MeV is not relevant to the analysis of the fundamental process. Experiment 83-17 is designed to study this macroscopic attenuation of 170 ± 30-MeV protons in the nucleus by studying the A-dependence of the (e,e'p) reaction.

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Electron-proton coincidences were measured on targets of carbon, aluminum, ^{58}Ni and tantalum with a 780-MeV electron beam from the MIT-BATES accelerator. Electrons in the energy range of 540-590 MeV were detected in the OHIPS spectrometer at 50.3° in coincidence with protons in the BIGBITE spectrometer in the energy range of 120-210 MeV and proton angles of 50.1°, 58.2°, 67.9° and 72.9°. The 50.1° proton angle corresponds to the angle for free scattering of an electron with an average three-momentum transfer of 610 MeV/c. Electron singles data were accumulated simultaneously with the coincidence data to provide an independent relative normalization.

The proton transmission is determined by comparing the angular dependence of the ratio of coincidence to singles cross sections to that predicted by Plane Wave Impulse Approximation calculations. The range in missing energy of 0-80 MeV is taken as the single-particle response. Figure III-3 presents the transmission extracted for each target. The transmission is not sensitive to the choice of single-particle potential for the nuclear bound states nor to the choice of off-shell electron-proton interaction.

The A dependence of the transmissions is fit with a classical calculation using a density-dependent effective nucleon-nucleon cross section. The solid lines in Fig. III-3 show the calculated attenuation for attenuation lengths at nuclear matter density (ρ_{NM} = 0.17 nucleons/fm^3) of 4, 5 and 6 fm. From this analysis, an attenuation length of 5 fm is deduced for proton energies of 150-210 MeV. Distorted-wave impulse approximation calculations require optical potentials with similar attenuation lengths. This is much larger than the simple $1/\rho_{NM}\sigma_{NM} \sim 2$ fm often used to estimate proton attenuation effects.

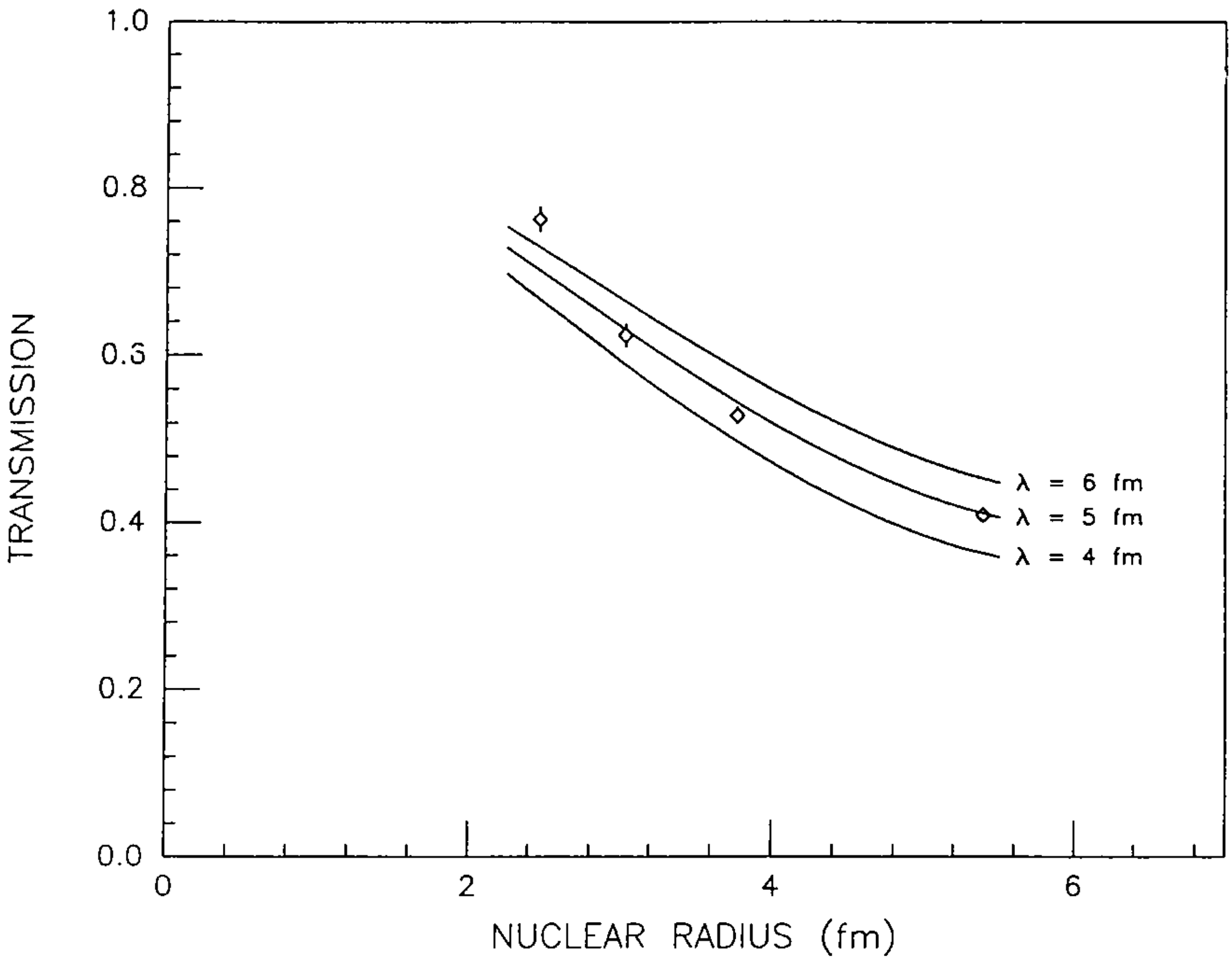

Fig. III-3. The transmission, defined as the experimental ratio of the coincidence to singles cross sections divided by the PWIA ratio, is plotted versus nuclear radius. The solid curves are classical attenuation calculations with three different nuclear matter attenuation lengths.

h. Electroexcitation of 8⁻ States in ^{52}Cr (B. Zeidman, D. F. Geesaman, R. D. Lawson,* D. I. Sober,† L. W. Fagg,†, G. C. Morrison,‡ O. Karban,‡ X. K. Maruyama,§ H. de Vries,¶ E. A. J. M. Offermann,¶ C. W. de Jager,¶ R. A. Lindgren,# and J. F. A. van Hienen**)

Inelastic electron scattering at incident energies between 170 and 260 MeV was used to identify and study M8 transitions in ^{52}Cr. A strong transition to an 8^- state at E_x=15.47 MeV was observed, as well as a number of weaker transitions. The results were compared with a single particle-hole shell-model calculation that uses a model space of the form $[(f_{7/2})^{11} \times g_{9/2}]_{8^-}$. The shell-model calculation and systematics in neighboring nuclei were used to determine the isospin of the observed states. The experimentally determined strengths exhaust 60.8% and 34.5% of the T=3 and T=2 sum rules, respectively. Publication of the results completes the electromagnetic section of the study.

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

The inelastic scattering of 162-MeV pions by ^{10}B was studied over the angular range 35° to 100° in the laboratory system and the data were analyzed with a model that incorporates shell-model wave functions into a distorted-wave impulse approximation formalism. Reduced transition probabilities were obtained for low-lying levels and compared with information previously reported. In addition, evidence is obtained for theoretically predicted levels with high spin, 5^+ and 6^+, that have not been observed previously. This phase of the program was completed with publication of the results.

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j. Design of a High-Momentum Spectrometer for CEBAF (B. Zeidman and L. Hardwood*)

A number of design options for the high-momentum spectrometer at CEBAF, HMS, have been investigated. This device will be utilized in a substantial fraction of the experimental program planned for Hall C. After consideration of experimental requirements determined by the users, the following design goals were established: p_{max} ~6 GeV/c; momentum bite, $(p_{max}-p_{min}/p_0)$ ~20%; momentum resolution, $dp/p<10^{-3}$; solid angle ~10 msr, minimum scattering angle <10°; scattering angle precision <0.1 mr; traceback accuracy for extended targets <1 cm. In addition to these goals, other features, e.g. compact focal plane normal to the central ray, are desirable but not essential if they are incompatible with the primary goals.

Consideration of the variety of design options used in other spectrometer systems, together with the experimental requirements, indicated that the optimum design would be QQQD or QQQDD, where Q is a quadrupole and D is a

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dipole. The dispersion (i.e. bend) plane is vertical while the transverse (i.e. scattering) plane is horizontal. The optical design is point-to-point in the bend plane and parallel-to-point in the scattering plane to accommodate extended targets without loss of scattering-angle precision.

The study has also considered utilization of components from existing spectrometers, e.g. those at SLAC, as well as construction of new elements. Since the design goals require large apertures and relatively small exterior dimensions in order to achieve the desired solid angle together with a 10° scattering-angle capability, it appears necessary to employ superconducting technology for the quadrupoles. The fields in these quadrupoles will be shaped by iron pole tips and generated by superconducting coils. It is not as yet clear if the same technology will be employed for the dipole(s); consideration of long-term cost and construction expenses will be the determining factors.

While considerable effort has already been expended in this design study, more detailed evaluation of costs, optimization of parameters, and engineering studies are still required before final decisions are reached. The preliminary studies have shown that it will be possible to achieve a design for the HMS that is compatible with realistic experimental requirements at a cost within budgetary constraints.

k. Short-Orbit Spectrometer for Hall C (H. E. Jackson and B. Zeidman)

Examination of the proposed program for Hall C at CEBAF reveals a major emphasis upon coincidence experiments involving the "core spectrometer" and a second arm capable of detecting particles with momenta <2 GeV/c with moderate energy and angular resolution, e.g. electroproduction of pions and kaons, color transparency, nucleon propagation. In all of these ANL programs a large acceptance will be necessary and, in addition, the detection of low-energy pions and kaons requires relatively short flight paths in order to minimize decay losses.

Accordingly, the ANL MEP group has accepted the responsibility, subject to budgetary constraints, for providing a short-orbit spectrometer that not only meets the needs of the experimental programs proposed by ANL, but is also capable of serving as a general-purpose second arm in a wide variety of experiments.

After investigating many spectrometer design options, it was decided that satisfactory results could be obtained either with a QQD design based upon the ANL-designed LAS spectrometer at LAMPF or with a duplication of the QD(-D) spectrometer, the MRS spectrometer currently under construction at LAMPF.
(Q denotes quadrupole, D denotes dipole, while the "-" sign indicates reverse-bend direction.) Inasmuch as the QD(-D) design is more compact and since detailed costing and engineering for this spectrometer is already completed, it was decided to proceed with the QD(-D) design for the Short-Orbit-Spectrometer (SOS).

The optical design is point-to-point in both the dispersive (vertical) and the transverse (scattering) planes. For a 1-mm target spot, the first-order resolving power is approximately 2200, while the angular resolution is <2 mr. Because of the reverse bend in the second dipole, there is a relatively small net deflection of the beam through the spectrometer, a property particularly useful for polarization measurements. Because of the strong-edge focussing, the optical length of the spectrometer is only ~7.4 meters. The rigid structural design, coupled with a compact focal-plane detector package, yields a device that is readily adapted to out-of-plane measurements, if required.

Further progress in implementing the SOS is contingent upon the development of the Hall C experimental program. Indications of the experimental priorities will be forthcoming during CY 1989.

B. INTERMEDIATE AND RELATIVISTIC HEAVY-ION PHYSICS

The aim of this program is to characterize the interaction between heavy ions and complex nuclei, and to study how the particle-particle interactions are affected by the nuclear medium. The energy region between 40-200 MeV/A constitutes a transition regime and has hitherto not been well studied. At the lower energies the interactions can be described in terms of nucleus-nucleus potential and collective variables for the system. At the higher energies nucleon-nucleon interactions dominate and the central collisions eventually lead to multifragmentation.

Aspects of the problem in the transition regime are addressed in an experiment at the low-energy beamline at the BEVALAC. The question of momentum and energy deposition in the composite system is studied, and the measurements should provide information on the limits to compound-like nucleus formation.

The interactions between heavy ions at relativistic energies are dominated by nucleon-nucleon interactions but the presence of the large number of nucleons in the heavy-ion reactions will give rise to collective effects in the excitation of the intermediate nucleon system. In the energy regime of 5-100 GeV/A (fixed target) the nuclear system will be highly compressed and achieve a large baryon density, while at even higher energies (available at RHIC) the central region is expected to be baryon poor.

The studies at the Brookhaven National Laboratory AGS are aimed at exploring global properties in relativistic heavy-ion collisions under the condition of high nuclear densities. Among the goals are a study of the effective temperature and energy density of the intermediate nuclear system, as well as the spatial size of the emitting source. These goals will be achieved by studying inclusive spectra of emitted particles and two-particle correlations.

a. Studies of Particle Production at Extreme Baryon Densities Produced in Collisions with ^{16}O and ^{28}Si Beams at 14.6 GeV/A (S. B. Kaufman, F. Videbaek, D. Alburger,* D. Beavis,* L. Birstein,* P. D. Bond,* C. Chasman,* Y. Y. Chu,* J. B. Cumming,* R. Debbe,* E. Duek,* S. Gushue,* Ole Hansen,* S. Katcoff,* M. J. LeVine,* M. Manscotti,* Y. Miake,* J. Olness,* L. P. Remsberg,* A. Shor,* M. Tanaka,* M. J. Tannenbaum,* M. Torikoshi,* J. H. van Dijk,* P. Vincent,* H. Wegner,* S. Nagamiya,† W. A. Zajc,† K. Kitamura,‡ T. Sugitate,‡ H. Crawford,§ M. Bloomer,¶ B. Cole,¶ J. Costales,¶ H. A. Enge,¶ L. Grodzins,¶ H. Huang,¶ R. J. Ledoux,¶ R. Morse,¶ C. Parsons,¶ M. Sarabura,¶ S. G. Steadman,¶ G. Stephans,¶ V. Vutsadakis,¶ D. Woodruff,¶ Y. Akiba,# H. Hamagaki,# S. Hayashi,# S. Homma,# Y. Ikeda,# K. Kurita,# T. Abbott,** and S. Y. Fung**)

The interaction of heavy ions at relativistic energies can result in the formation of highly-excited nuclear matter in a region of energy density where it is expected that qualitatively new phenomena may occur. Many questions exist about the exact energy densities that can be achieved in such collisions and as to the experimental signatures of the expected new phenomena. The objective of this experiment, the first fully-mounted heavy-ion experiment at the AGS, is to study semi-inclusive spectra of p, π, K, d, using a single-arm magnetic spectrometer. These distributions are measured under a variety of conditions relating to energy-and-multiplicity flow which are a measure of impact parameter and thus of the centrality of the collision.

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To date, the experiment has had several periods of running with the complete setup. A 4-week production run with ^{16}O ions took place in June 1988 followed by a 2-week run with protons and one week with ^{28}Si ions at the end of 1988. A complete set of data has been obtained for projectiles of Si, O and protons on targets of Au, Cu and Al covering an angular range of 5 to 55 degrees with the single-arm spectrometer.

The analysis of the ^{28}Si data is well underway. The previously reported large ratios of K^+/π^+ over what is expected from proton-induced reactions has been confirmed. Comparison to the FRITIOF model suggest that this is indeed due to an enhanced production of kaons, and not a suppression of pions. This comparison also indicates that the measured K^-/π^- ratio, though much lower than the K^+/π^+ ratio, is larger than expected. The comparison to the proton- and ^{16}O-induced data will provide essential information towards an understanding of the large production rate. Such understanding does not exist presently, but must include the effect of the nuclear medium on the initial scattering process and the later expansion process. The measured momentum spectra for various particles (p,π,k) are well described as an exponential function in the transverse mass ($m_t = [p_t^2 + m^2]^{1/2}$). Such distributions are expected for the emission from a hot thermal system.

The group at Argonne has had the responsibility of coordinating the electronic signals from the various partitions of the experiment and of constructing the logic and hardware for the on-line triggering. Work has been done on a generalized trigger supervisor, computer controlled through a VME interface. This device controls and coordinates the first- and second-level triggers for up to 16 partitions, each with 8 trigger possibilities. Triggers can be individually enabled and downscaled. This hardware was used during the November 1988 proton run, performed well and made a significant improvement to the ease and confidence in which trigger conditions were controlled.

During the running periods we also participated in the calibration and running of the zero-degree calorimeter. This is an iron calorimeter subtending a few degrees centered at zero degrees. A dedicated calibration experiment was performed which studied the response of the device to charge- and mass-identified ions from protons to ^{16}O and ^{28}Si. The device exhibits good linearity over the range 50-220 GeV with a reduced resolution σ/E of $0.75/E^{1/2}$.

Investigation of the correlations between the energy deposited in the calorimeter and transverse neutral energy and multiplicity show a one-to-one correspondence between large transverse energy and multiplicity (central collisions) and a near absence of energy deposited in the calorimeter. Furthermore, a simulation of the fraction of the projectile which does not interact with the target for given impact parameters under simple geometric assumptions, is able to give a good account of the observed spectra. A further analysis along these lines, which includes the permanent deformation of a projectile, has been done. The effect with ^{28}Si is fairly small but will reduce the agreement between the simple geometric model and the data.

The off-line analysis for E802 is set up within the framework of Analysis-Control, a software package taken over from the CDF experiment at FNAL. It has been further improved and optimized for the specific E802 application and is now being routinely used for all the production analysis of the experimental data.

b. Binary Breakup in the Reaction $^{56}Fe + ^{197}Au$ at 200 MeV/A

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The reaction of 100-MeV/A ^{56}Fe with ^{197}Au to give two heavy fragments was studied at the Lawrence Berkeley Laboratory BEVALAC. Coincident fragments were detected and their energy, mass (via time-of-flight) and angle measured using gas detectors with large solid angles. Energetic light charged particles were also detected in coincidence with the heavy fragments, using arrays of plastic scintillator phoswich telescopes. The objective was to study the momentum and energy transfer in nucleus-nucleus collisions at intermediate energies (50-100 MeV/A). The momentum transfer ($p_{||}$) was calculated for each event from the momenta and angles of the coincident fragments, assuming binary breakup. For small $p_{||}$, corresponding to angles between the fragments close to 180°, most of the events have total mass close to that of the target, and their total kinetic energy is consistent with binary fission of excited near-target residues. These events are interpreted as the result of peripheral collisions in which little momentum and energy is given to the target, and fission competes with neutron evaporation in the subsequent de-excitation process. This view is confirmed by the low multiplicity of light charged particles in coincidence. As $p_{||}$ increases, the summed fragment mass decreases, while the average total kinetic energy remains unchanged and the charged-particle multiplicity increases, indicative of more central collisions with greater momentum and energy transfer. Calculations based on the Intranuclear Cascade and Statistical Models indicate that these events can be accounted for by binary fission toward the end of a long evaporation chain of a highly-excited target residue. However, the possibility that a multifragmentation process (emission of >2 heavy fragments) also contributes cannot be excluded.

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c. Fragment Emission in the Reaction of Nb with ^{197}Au at 50-100 MeV/A

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The new Pagoda detector system was used to study fragment emission in the Nb + Au reaction with Nb beams of 50, 75, and 100 MeV/A at the BEVALAC. A forward-angle 34-element hodoscope detected projectile-like fragments, eight gas telescopes (multiwire proportional counters and ionization chambers) detected medium- and heavy-mass fragments, and scintillator phoswich telescopes detected energetic light charged particles. Fragment identification was done by means of energy loss in different detectors and time-of-flight. Three broad classes of fragments were identified: intermediate-mass fragments (IMF); fission fragments (FF); and heavy residues (HR). The data indicate that these three types originate in collisions with different impact parameters. Fission occurs following the most peripheral collisions, with little momentum transfer. At smaller impact parameters, the excited target residue evaporates particles and, because of its reduced fissility, results in a heavy residue rather than fissioning. The most central collisions result in large energy and momentum transfer and large particle multiplicities, including the IMF's. The impact-parameter information was derived from the projectile-like fragment detected in the forward hodoscope; smaller impact parameters lead to lighter projectile remnants. The multiplicities of light charged particles also serve as a signature of the violence and hence the centrality of the collision. These features are similar at all three beam energies. However, the momentum transfer for peripheral collisions, obtained from the fission-fragment folding angle, decreases with increasing bombarding energy.

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d. Medium Energy ACP-System (F. Videbaek)

A microprocessor farm consisting of the Fermilab Advanced Computer Project (ACP) system with 10 processors has been set up with the medium-energy VAX 11/750. Each processor has a cpu power equivalent to approximately 0.5 of a VAX 11/780. The system software has been obtained from FNAL and is relatively easy to use. The system is well suited for cpu-intensive event analysis and Monte Carlo simulations.

The ACP-system was installed during summer 1988 and has been operational since September 1988. It has been used extensively for event simulation of relativistic heavy-ion collisions using the FRITIOF code. The event-analysis software for experiment E802 is currently being implemented.

It is envisioned that the system in the future could be controlled by a dedicated VAX-3200 workstation to minimize the overhead currently imposed by the VAX 11-750.

C. WEAK INTERACTIONS

The main goals of the weak-interactions program are to verify the implications of the standard model of electroweak and strong interactions and to discover its inadequacies. The success of the standard model in explaining phenomena over a large range of energies is reflected in the diverse experiments conducted in this program. Experiments to measure quantities important to theories of astrophysics and cosmology form an increasing fraction of the work of this program.

The second year of production-data running for the neutrino oscillations was completed during three LAMPF beam cycles in 1988. The data are of high quality and we expect to improve our recently-published limits on neutrino oscillation parameters. The two-year data set now in hand is being used to search for other possible rare phenomena which could indicate the necessity for extensions of the standard model.

Neutron-beta-decay experiments at Grenoble have been a long-time component of the program. A new result for the directly-measured neutron lifetime was published this year. The measured lifetime is consistent with the previously-measured neutron asymmetry parameters. A final paper on the asymmetry parameters was also published. An improved lifetime measurement will be performed in 1989. A new experiment to test time-reversal invariance in neutron decay is now being developed.

An experiment to better determine the Cabibbo angle by measuring the partial lifetime from the superallowed decay of ^{10}C is progressing. A new technique was developed and will allow a more precise correction for the effects of positron annihilation radiation. This experiment should improve our knowledge of a critical Kobayashi-Maskawa parameter and allow a better test of the unitarity of the currently favored three-dimensional version of this theory.

An experiment to help determine the rate of solar Hep neutrino production was completed at ILL. A new experiment to measure the astrophysically interesting $D(D,\gamma)T$ cross section at low energies using the new ATLAS ECR source has begun this year. This work makes use of the unique capability of the ATLAS source to be a pulsed low-energy accelerator.

a. <u>Neutrino Oscillations at LAMPF</u> (S. J. Freedman, J. Napolitano, J. Nelson, R. Carlini,# C. Choi,† J. Donahue,* S. Durkin,§ A. Fazely,† B. Fujikawa,‡ G. T. Garvey,* R. Harper,§ R. Imlay,† K. Lesko,‡ T. Y. Ling,§ R. D. McKeown,‡ W. Metcalf,† J. Mitchell,§ T. Romanowski,§ V. Sandberg,* E. Smith,§ and M. Timko§)

Experiment E-645 is a search for $\bar{\nu}_e$'s production at the LAMPF beamstop. The beamstop is a copious source of ν_μ, $\bar{\nu}_\mu$, and ν_e but a $\bar{\nu}_e$ signal would suggest transformation of one of the other neutrino types. Our experiment employs a 20-ton tracking detector made from 40 layers of liquid scintillator and 80 layers of proportional drift tubes. The neutrino detector is completely surrounded by a 15-cm-thick liquid scintillator active cosmic-ray shield and a 15-cm thick passive lead shield built by ANL. The entire system is operated in a tunnel, under 2500 g/cm^2 of overburden, about 24 meters from the LAMPF beamstop. The detection method is by inverse beta decay on the proton and the experimental signal is the track of a final-state positron (maximum energy about 52 MeV) having the correct dE/dx and range. In addition each scintillator counter layer is covered with a thin sheet of gadolinia allowing us to identify the final-state neutron as a delayed-capture gamma-ray signal in the scintillators.

The experiment was exposed to the beamstop neutrino beam for all three cycles in 1987 and data were collected for about 80 days. The 1987 data have been analyzed, and without having to resort to neutron detection no excess $\bar{\nu}_e$ signal was found, although the signal of ν_e nucleus scattering is observed at the expected level. The experimental sensitivity is sufficient to rule out an interesting range of neutrino oscillation parameters. A report of this work was recently published. The experiment contradicts the evidence for neutrino oscillations that was reported from experiments at CERN and BNL.

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Three additional cycles of data collection were accomplished in 1988 and the data are now being analyzed. The experiment is scheduled to continue for three more cycles in 1989. The data already in hand are being used to search for other possible rare processes (for example axions and $\pi^0 \to \nu\bar{\nu}$) in addition to neutrino oscillations.

b. Search for Cosmic-Ray Point Sources (S. J. Freedman, J. Napolitano, J. Nelson, F. L. H. Wolfs, B. Fujikawa,* K. Lesko,† D. Krakauer,‡ and the Los Alamos Cygnus collaboration: University of California at Irvine, and Los Alamos National Laboratory)

We have continued our development of inexpensive cosmic-ray shower-array counters that could be used in an expanded array at Los Alamos. The newest detector is housed in a 2-m high .7-m diameter cylindrical PVC plastic tank normally used for underground liquid storage. About 15 cm of liquid scintillator covers the bottom of the tank and scintillation light is detected with a single 12.5-cm diameter spherical phototube at the top. The time resolution is slightly better than a nanosecond (σ). The new tanks will be tested in a realistic outside environment this winter.

Work continues on better utilizing the E645 shield as a coincident muon detector for the Cygnus array.

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c. <u>Neutron Beta Decay</u> (J. Last, S. J. Freedman, M. Arnold,* J. Döhner,* and D. Dubbers,†)

The final analysis of our recent direct lifetime measurement was completed and a paper was published reporting the final result, τ=876±21 sec. This lifetime is consistent, within errors, with our previous determination of g_A/g_V, from measurements of the beta asymmetry of the neutron.

A technical paper describing details of the PERKEO beta spectrometer was published as well as a detailed paper on the final results of our previous measurements of the beta asymmetry.

An improved version of the lifetime experiment, using a chopped beam of neutrons, was developed in 1988. The experiment is now being prepared at Grenoble and it will be run beginning in February 1989 for two 40-day cycles. We expect that the improvements will result in at least a factor-of-two reduction in the experimental error in the directly-measured neutron lifetime.

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d. <u>The Vector Weak Coupling and ^{10}C Superallowed Beta Decay</u> (M. Kroupa,* S. J. Freedman, R. Holzmann, J. Napolitano, J. Nelson, and P. Barker,†)

The best values of the weak vector coupling constant g_V now come from $0^+ \rightarrow 0^+$ superallowed nuclear beta decay. In principle the best experiment in nuclei is the decay of ^{10}C because of its relative insensitivity to radiative corrections. Unfortunately the experimental error in the branching ratio of the ^{10}C ground state to the 0^+ excited state of ^{10}B is large and the best determinations now come from higher-Z systems. We are measuring this branching ratio to 10^{-3} with an experiment being conducted at the EN tandem of Western Michigan University in Kalamazoo. The experiment determines the branching ratio from measurements of the cascade γ-rays following beta decay.

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The critical γ-ray efficiency calibration uses an in-beam method in which inelastic scattering on ^{10}B is used to excite the 0^+ level. By measuring the γ-rays in coincidence with backscattered protons of the right energy, the necessary relative calibration is accomplished in exactly the same geometry as the beta-decay measurement.

The experimental technique was refined in 1988 and some production running was completed at the Western Michigan University Tandem. The combined statistical and systematic error of these measurements is about 1.0%. The analysis to determine the branching ratio is proceeding. The most serious systematic error is from pileup of 0.511-MeV annihilation radiation which, by chance, gives the same energy as the weakest photon in the cascade of interest. A new procedure to make this critical correction, using positrons from ^{19}Ne decay, was developed this year. This method will reduce the combined error to below 0.3% for the data already collected. We plan to publish our present results before proceeding to reduce the error further.

e. The Decay of Polarized Mirror Nuclei (S. J. Freedman, J. Napolitano, F. L. H. Wolfs, W. Haeberli,* P. A. Quin,* and K. Coulter†)

The measurements of beta asymmetry parameters in selected nuclear systems is sensitive to many important properties of the weak interaction. In some decays the beta asymmetry is sensitive to possible and expected induced currents and the strength of the vector coupling constant. We continue to apply the method of polarizing radioactive nuclei in reactions with polarized projectiles in order to study these important effects.

An apparatus to measure the beta asymmetry in certain mirror decay systems is being constructed at Argonne. The detector incorporates a large NaI(Tl) detector and two plastic scintillator telescopes. The NaI surrounds the target and has inserts for the beta telescopes. Two large coils provide a uniform magnetic field of up to $\simeq$ 1.5 kG. The absolute size of the beta asymmetry for mirror decays that have an excited-state pure Gamow-Teller

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branch will be studied with this system, the excited-state decays being identified by γ-ray coincidences. The asymmetry observed for the transitions to the excited states is used to measure the polarization of the decaying nucleus, since the size of the asymmetry in Gamow-Teller decays is determined by the spins involved. With the polarization measured we can determine the groundstate-to-groundstate asymmetry. Combined with measurements of the beta-decay lifetime these measurements can be used to determine g_V for these transitions. Measurements of g_V in mirror decay have previously been made for the neutron, ^{19}Ne, and ^{35}Ar; we hope to extend these measurements to other mirror decay systems.

f. Search for Short-lived Axions Emitted from Neutron Capture on Protons (S. J. Freedman, J. Last, M. Arnold,* J. Döhner,* and D. Dubbers,†)

In order to explain the sharp positron emission lines seen in particular heavy-ion collisions at the GSI, several theorists have attempted to modify the standard axion model making the axion a candidate for the unexplained phenomena. The new "viable" axion would be very short lived and have a mass larger than two electron masses. A particularly sensitive way to search for this new particle is the isovector transition in n+p capture. The variant axion would produce an e^+e^- emission signal far larger than that expected from ordinary direct-pair emission. Earlier we searched for this enhanced-pair emission during the course of our experiments to measure the neutron lifetime. The final analysis of this experiment is now completed and a paper describing the experiment and the limits on "viable" axion production was recently published.

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g. Determination of $^3He(p,e^+\nu)^4He$ from Measurements of $^3He(n,\gamma)^4He$

(F. L. H. Wolfs, S. J. Freedman, J. Napolitano, J. Nelson, S. Dewey,* and G. Greene*)

The highest energy neutrinos produced in the sun, with energies up to about 19 MeV, come from the weak capture of low-energy protons on trace amounts of ^3He. With solar-neutrino detectors capable of measuring neutrino energy being developed, we now have the opportunity to detect the rather small expected flux of these energetic neutrinos since they can be distinguished from the higher flux of low-energy neutrinos from ^8B beta decay. Measurements of these ^3He neutrinos ("Hep neutrinos") would provide an entirely new handle on the solar-neutrino problem because the Hep neutrinos come from a different region of the sun than do the ^8B neutrinos.

It is not possible to measure the $^3He(p,e^+\nu)^4He$ reaction directly but it is possible to make reliable estimates from the related cross section for $^3He(n,\gamma)^4He$ at low energies. At low energies this capture is mostly M1 and thus simply related to the weak process. The experimental value for the neutron capture cross section was obtained in three experiments, two are consistent with σ=60 μbarns (the error is about 20%), while one implies σ=29±9 μbarns, in disagreement.

We measured the critical capture cross section in a run at Grenoble during September and October 1988. The experiment was straightforward; we measured the cross section using a ^3He-gas target and a large shielded NaI(Tl) detector. The gas cell was filled with a combination of ^3He and N_2 and we calibrated to a well-known nitrogen capture reaction cross section. The data phase of the experiment was very successful and the data are now being analyzed. We expect that the final error will be between 5 and 10%.

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h. Neutron Absorbing Materials for Low-Background Neutron Experiments (J. Nelson, F. L. H. Wolfs, and J. Last)

In the course of high-precision experiments with low-energy neutrons we have searched for convenient materials which absorb neutrons without producing background gamma rays. One common material for this purpose is ^{6}LiF but in its usual form, a powder, it is difficult to fabricate into the complicated shapes usually required for collimators or shields. We have devised a simple method of painting surfaces with a special compound containing ^{6}LiF which, after heat treatment, produces a hard durable surface containing only trace amounts of light elements (hydrogen and carbon). We have embarked on a project to evaluate this material and other materials that can be employed for this purpose.

We intend to test various compounds containing ^{6}Li at the reactor facility at the National Institute of Standards and Technology at Gaithersburg this winter. We are hopeful that these tests will allow us to evaluate the utility of the various compounds under study.

i. Nuclear Astrophysics and a Measurement of the D(D,γ)^{4}He Reaction at the ATLAS ECR Ion Source (T. F. Wang, F. L. H. Wolfs, S. J. Freedman, J. Nelson, R. Pardo, R. Dunford, and J. Last)

The D(D,γ)^{4}He cross section at extremely low energies is an essential input parameter for theories of nucleosynthesis in cosmology and astrophysics. This reaction is difficult to estimate reliably because it depends sensitively on the D-state admixture in ^{4}He and at low energies the cross section is extremely small. Previous experiments which observe the 23.6-MeV capture γ-ray have been hampered by the large background from neutron capture following the dominant D(D,n)T reaction and from cosmic-ray backgrounds. We intend to measure this reaction at deuteron energies down to 50 keV using a pulsed beam of deuterons from the new ATLAS Electron Cyclotron Resonance ion source. The pulsed beam combined with a time-of-flight system will allow us to significantly reduce both neutron-induced and cosmic-ray backgrounds. In addition the impressively large intensity of the ECR source will allow high statistics measurements. We believe that the unique capability of a high-intensity pulsed ECR source will be useful in other low-energy cross-section measurements of astrophysical interest.

j. A New Measurement of Possible Time-Reversal Non-Invariant Correlations in Neutron β-Decay (S. J. Freedman, J. Last, J. Nelson, F. L. H. Wolfs, K. Coulter,* and D. Krakauer†)

The decay probability for polarized neutrons is expected to contain a correlation of the form: $D(\mathbf{J} \times \bar{p}_e \cdot \bar{p}_\nu)$. In principle this correlation violates time-reversal symmetry but final-state interactions, mainly through the weak-magnetism effect, give rise to a non-zero D of about $\simeq 1 \times 10^{-5}$. A different value of D could signal time-symmetry violation. The experimental limits on D are about 10^{-3} from experiments completed more than a decade ago. We are planning for a new experiment aimed at improving the sensitivity by one-to-two orders of magnitude. The experiment will capitalize on the significant improvements of polarized neutron beam intensities obtained over the years at the ILL. We are presently developing a large-area silicon detector that will be used to detect both electrons and protons.

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k. Measurement of the Electric Dipole Moment of the Neutron (M. S. Freedman, M. Peshkin, G. R. Ringo, and T. W. Dombeck*)

The ultimate 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. Since 1970 it has been clear that this measurement can best be done on ultracold neutrons (UCN) which have a velocity <7 cm/sec and can be stored in a system for several minutes. We propose to do this using a pulsed neutron source. We would keep the inlet to the system 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 neutrons from a moving lattice designed so that the reflected neutrons are almost stationary in the laboratory system.

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The advantage of this is that it avoids the problems of extracting the very delicate UCN from the different environment near 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.

We now believe though that we should consider seriously doing the experiment with a UCN interferometer. This offers, in principle, a higher sensitivity than the NMR method now being used by other groups. It would certainly have different systematic errors which would make it interesting even if it gave no gain in sensitivity.

We have a number of different types of such interferometer under consideration and are studying their relative advantages. A major consideration in those designs is the suppression of systematic errors, particularly the magnetic field produced by motion of the neutrons in an electron field, the vxE effect. The basic strategy all our designs use is to polarize the neutrons and then accelerate them by a neutron field gradient acting on the electric dipole moment, which is parallel to the spin. This acceleration, after a storage time of more than 100 seconds, will produce a phase shift relative to a reference beam. This phase shift should be detectable by ordinary interferometric methods.

Preliminary estimates indicate that this method, using known technology, may be competitive with the Ramsey method at the level of 10^{-26} cm times the electron charge, and it would have different systematic errors. Other, more speculative designs may in principle achieve a sensitivity as fine as 10^{-30} e-cm if that should become necessary.

IV. THEORETICAL NUCLEAR PHYSICS

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

A. Nuclear forces and sub-nucleon degrees of freedom.
B. Intermediate energy physics with pions, electrons and nucleons.
C. Heavy-ion interactions.
D. Nuclear structure studies, principally in deformed and transitional nuclides.
E. Relativistic mean-field theories.
F. Quantum mechanics with magnetic charges or flux lines.

A. NUCLEAR FORCES AND SUBNUCLEON DEGREES OF FREEDOM

(A. R. Bodmer, F. Coester, T.-S. H. Lee, S. C. Pieper, R. B. Wiringa, V. R. Pandharipande,* and others)

Detailed, quantitative studies of the consequences of model Hamiltonians for nuclear systems are an important aspect of our work. In the last year we completed our most recent study of nuclear and neutron matter using realistic two- and three-nucleon potentials. The resulting equation of state was used to study neutron star structure and found to be consistent with current observational data. The real part of the optical potential for nucleons in nuclear matter was also extracted for these Hamiltonians, the momentum and density dependence is consistent with intermediate-energy heavy-ion collision data.

We have also continued our calculations of light nuclei (^{3}H, ^{3}He, and ^{4}He) with the same potentials and have made significant improvements in our variational wave functions. However, we are now devoting major efforts to computing the ground states of heavier nuclei: ^{6}Li, ^{6}He, ^{8}He, ^{16}O and ^{40}Ca. These calculations are also being done with the same interactions and thus we will have a consistent description of a large range of nuclear systems. We expect these results to place significant constraints on the assumed nuclear interactions, particularly the three-nucleon potential.

Much of the quantitative information that will determine the success or failure of competing models of nucleon interactions will come from electro-magnetic probes. Observed quantities are directly related to matrix elements of the electric charge and current densities. A valid interpretation requires mutually consistent representations of the current operators and the target wave functions. Our work on the form factors of the deuteron and three-nucleon systems should provide a continuous transition between the regime of low momentum transfer and the asymptotic regime governed by perturbative QCD.

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Studies of the binding energies of hypernuclei and their interpretation in terms of Λ-nuclear interactions are being continued. During the past year a comprehensive study of the binding energies of the s-shell hypernuclei and of the Λ well depth (Λ binding in nuclear matter) has been published. A short review of our work on hypernuclei was prepared and published. Work is continuing on α-cluster and multi-Λ hypernuclei and on charge symmetry breaking interactions.

a. Dense Nucleon Matter Equation of State (R. B. Wiringa, A. Fabrocini,* V. Fiks and M. Wolff)

The dense nucleon-matter equation of state (EOS) plays an important role in high-energy heavy-ion collisions, supernovae, and neutron star structure. We have completed a set of theoretical calculations of nuclear and neutron matter for densities from 0.5 to 10 ρ_0 (ρ_0 = 0.16 fm^{-3} is the experimental equilibrium density of nuclear matter). These studies use a Hamiltonian containing either the Argonne v_{14} or Urbana v_{14} two-nucleon potential (which fit NN scattering data and deuteron properties) with and without the Urbana VII three-nucleon potential (which fits the binding energy of ^3H and ^4He in variational Monte Carlo calculations). Variational wave functions and hypernetted-chain integral equations are used to compute the matter binding energy as a function of density, $E(\rho)$.

The addition of the three-nucleon potential to the Hamiltonian significantly improves the saturation behavior of nuclear matter. The models studied here saturate at 1.1-1.2 ρ_0, compared to 2 ρ_0 for the two-nucleon potentials alone. Consequently the nuclear and neutron matter EOS are significantly stiffer than for two-body potentials only. In the Argonne-v_{14}-plus-Urbana-VII case there is also a local softening of the neutron matter EOS near 2 ρ_0 which may indicate a phase transition to a neutral pion condensate. This effect requires the presence of a realistic two-pion exchange three-nucleon potential, and is sensitive to details of the core of the two-nucleon potential.

We have also computed the EOS for β-stable matter (neutrons, protons, electrons and muons) and the corresponding neutron star properties. The EOS is softer than for pure neutron matter, but the neutral pion condensate is

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washed out. The maximum supportable neutron star mass is 2 $M_\odot$ for the nuclear Hamiltonians containing the three-nucleon potential, as compared to 1.5 $M_\odot$ for two-body potentials only. The canonical 1.4 $M_\odot$ star has a correspondingly larger radius of 10-11 km when the three-nucleon potential EOS is used compared to less than 8 km with two-nucleon potential only. The β-stability condition acts to keep the stellar radius, crustal thickness, and moment of inertia smaller than in the pure neutron matter case. The predicted neutron star properties are in good agreement with present observational data.

This work has been published in Phys. Rev. C 38, 1010 (1988). The wave functions obtained were also used as input to a study of the single-particle potential in dense matter (see next section). Future work should include an investigation of the superfluid gap in low-density neutron matter which plays an important role in the coupling of the neutron star core and crust. This would involve extending the EOS to densities as low as 0.05 ρ_0.

b. Single-Particle Potential in Nuclear Matter (R. B. Wiringa)

The real part of the optical potential $U(\rho,k)$ for nucleons and holes in nuclear matter has been calculated microscopically using Hamiltonians containing realistic two- and three-nucleon potentials. The optical potential had been computed earlier by Friedman and Pandharipande for densities up to ρ_0 using the variational method and two-nucleon potentials only. The dense nucleon matter equation of state (EOS) studies (Sec. IV.A.a.) provide the wave functions necessary for calculating $U(\rho,k)$ at densities up to 3 ρ_0, and momenta up to 5 fm^{-1}. Boltzmann-Uehling-Uhlenbeck (BUU) simulations of heavy-ion collisions require knowledge of the optical potential at these higher densities.

The variational wave function is written as the product of a two-body correlation operator G acting on a Fermi-gas wave function $\Phi[n(k)]$, where for the ground state the occupation $n(k) = n_0(k)$ is just a Fermi sea filled to k_F. To describe one-quasiparticle (hole) states at a given density we use $n(k) = n_0(k)+\delta_{pk}$ for $p>k_F$ ($-\delta_{qk}$ for $q<k_F$) and keep the correlation operator G fixed. The single-particle (hole) energies $e(k)$ are just the difference between the energy expectation value with these wave functions and the ground-state energy. The real part of the optical potential $U(k)$ can then be found, as well as other quantities like the energy-dependent effective mass $m^*(e)$.

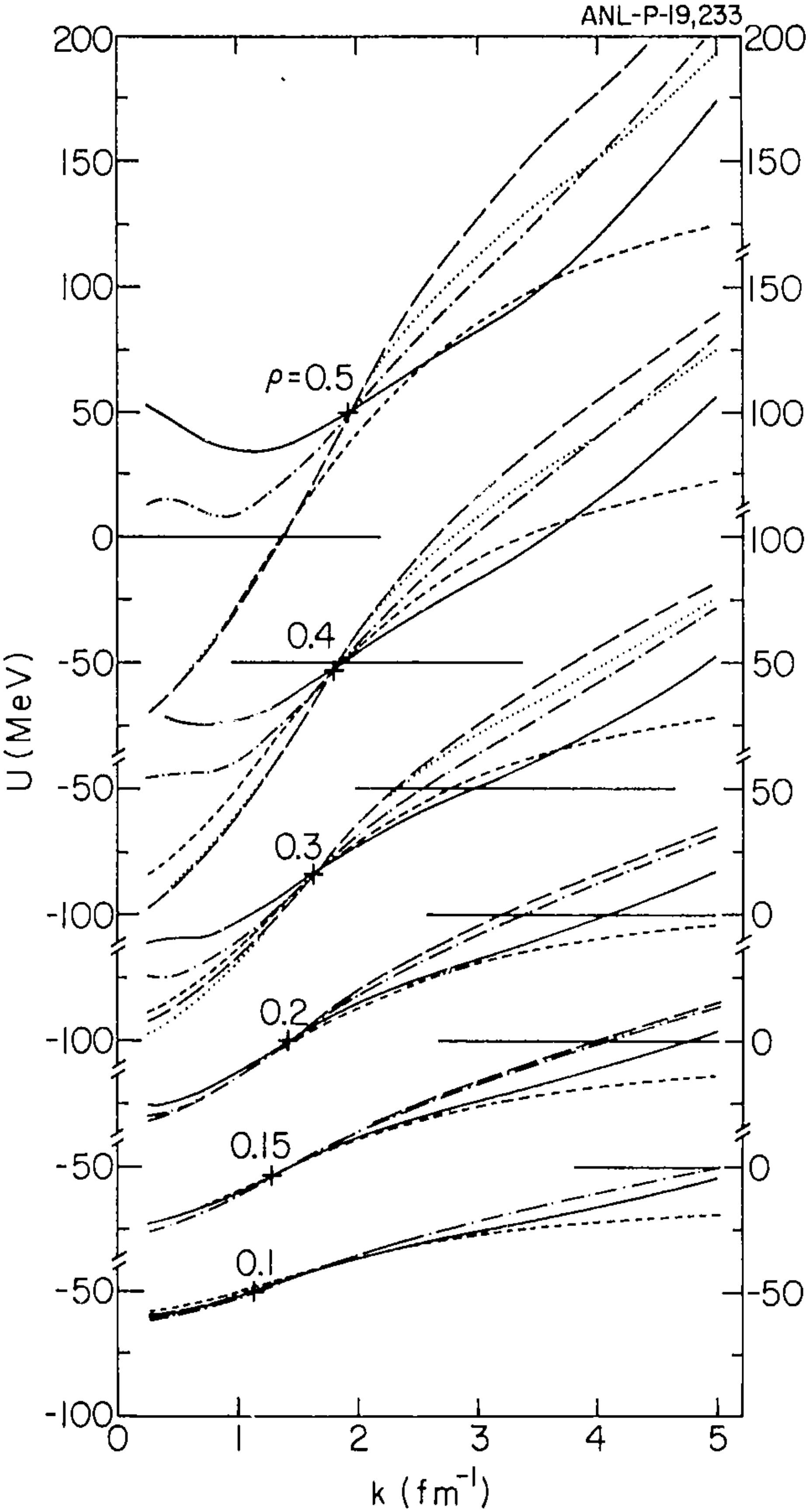

Fig. IV-1. The single-particle potential U(ρ,k) in nuclear matter for several different Hamiltonians.

The calculated $U(\rho,k)$ is shown in Fig. IV-1 for several different Hamiltonians, including the Argonne v_{14} two-nucleon potential plus Urbana VII three-nucleon potential (solid line), the Urbana v_{14} two-nucleon potential plus Urbana VII (dash-dot line) and the Urbana v_{14} plus TNI density-dependent two-nucleon potential (dashed line). Also shown (short-dashed line) is a simple parameterization suggested by Gale, Bertsch and Das Gupta, which reproduced experimental heavy-ion collision data in a BUU simulation. It appears that when the density and momentum dependence of U are taken into account, the heavy-ion collision data are consistent with the microscopic EOS predicted by Hamiltonians fit to two- and three-nucleon data. This is in contrast to earlier interpretations of the data as evidence for a very much stiffer EOS.

This work has been published in Phys. Rev. C 38, 2967 (1988). Future work should include a microscopic calculation of the imaginary part of the optical potential.

c. Variational Monte Carlo Calculations of Few-Body Nuclei
(R. B. Wiringa, V. R. Pandharipande* and J. Carlson†)

Variational Monte Carlo studies of ^{3}H, ^{3}He, and ^{4}He are continuing, and we have begun calculations of the ground states of ^{6}He, ^{6}Li, and ^{8}He, and of some low-energy reactions of astrophysical interest. In the past year we have developed better variational wave functions which include pair correlations containing six operator terms (central, spin, and tensor, and each of these times isospin) compared to only three operator terms in previous correlations. The new trial functions are still not as good as the 34-channel Faddeev wave functions in the three-nucleon system, but are variationally superior to the 5-channel Faddeev wave functions of a few years ago. We have also significantly improved the speed of the codes and implemented a more efficient variational search procedure.

The six-nucleon system has been studied previously by other methods, but only in a three-body (alpha-plus-two-nucleons) approximation. Our goal is to calculate the ground-state binding energy and other properties using a

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realistic Hamiltonian and treating the nucleus as a six-body problem. The trial wave function is taken as that of a four-nucleon s-shell (alpha) cluster coupled to J = 0, T = 0, and two p-shell nucleons that are LS coupled to either J = 0, T = 1 for ^{6}He or J = 1, T = 0 for ^{6}Li. Pair correlations with six operator components act between all fifteen pairs and each of the two p-shell nucleons also has a central p-wave correlation to the center of mass.

The code for calculating the ground states of ^{6}He and ^{6}Li is now running. The ^{6}Li calculation requires around 50 times more floating point operations (FLOP) per energy evaluation (1.8 seconds on a single processor Cray), but vectorizes better than for ^{4}He (.09 seconds) so the calculation is possible with our current allocations of Cray time. We have also made timing tests for a ^{8}He code, which requires about 15 times more FLOP per energy evaluation (20 seconds) than ^{6}Li, and should be feasible with an increased allotment of Cray time. The six-nucleon problem will be pursued vigorously during the coming year.

We are also interested in light-ion reactions, such as ^{3}He(n,γ)^{4}He, ^{3}He(p,e+ν)^{4}He, and ^{2}H(d,γ)^{4}He, at astrophysical energies. A recent experiment on the first reaction has been made by the Argonne weak interactions group and their data are currently being analyzed. The second reaction is the source of the highest-energy neutrinos produced in the sun, and thus a component observed in all solar neutrino detection experiments. In previous theoretical work the ground states of ^{3}He and ^{4}He have been represented by shell-model wave functions. We have a better description of the ground states, but we need to learn how to handle the continuum states in a reasonable way. A first set of calculations has been planned and will be pursued during 1989.

d. Ground States of Closed-Shell Nuclei (S. C. Pieper, R. B. Wiringa, and V. R. Pandharipande*)

The nuclear many-body problem has generally been explored only at its extremes, the few-body nuclei ^{2}H, ^{3}H, ^{3}He, and ^{4}He, and nuclear matter. For these cases, reliable calculations with realistic potentials are available. However, there are very few calculations of heavier nuclei in which the nucleus is considered as a system of nucleons interacting with realistic potentials. Those that do exist have been made with relatively out-of-date two-nucleon potentials and no three-nucleon potential.

We are computing the ground states of the closed-shell nuclei ^{16}O and ^{40}Ca with the same interactions that are being used in the light nuclei and nucleon matter studies (IV.A.a. and IV.A.c.). We are using a variational Monte Carlo technique in which the variational wave function is written as a symmetrized product of spin, isospin, and tensor correlation operators acting on a Fermi-Jastrow wave function containing only spatial correlations. The resulting wave function is thus also very similar in structure to those used in the preceding sections. The expectation value of the Hamiltonian is computed using a cluster expansion of the operator terms and the necessary (3-A dimensional) integrals are done by the Metropolis random walk. During FY 1988 we wrote the three- and four-cluster and the three-body potential parts of the program. Because of the large amounts of time required by these calculations, we put considerable effort into optimizing the program for vector computers. The program runs at 125 MFLOPS on a single processor of a Cray 2S. The program was debugged by using various internal consistency checks and by reproducing our calculations of the alpha particle. We have also made extensive variational searches for ^{16}O. We found that the four-cluster contribution to the kinetic energy is essential for confining the variational search to physically reasonable parameters. This is an unfortunate result because we had hoped to make the searches using only the contributions up to the three-cluster level; including the four-cluster terms increases the computer time by a factor of 25.

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The variational searches are not yet complete; preliminary results for ^{16}O show the same or less binding per nucleon than is obtained with the same potentials for ^{4}He. Previous calculations of ^{16}O (and ^{40}Ca) have also given this result.

e. Distribution of the Number of Nucleons in a Subvolume of a Nucleus
(S. C. Pieper, V. R. Pandharipande* and G. A. Baym*)

One of the quantities measured in the bombardment of nuclei by ultra-relativistic protons is the distribution of transverse energy (E_T). In a simple model, this can be related to a folding of the distribution of E_T produced in proton-proton collisions and the distribution of the number of nucleons encountered by the proton as it passes through the nucleus. We used a preliminary version of our program for ground states of nuclei (Sec. IV.A.d.) to compute the latter distribution. We found that the distribution was much narrower than that given by Poisson statistics. This is to be expected because of Pauli statistics and the repulsive core in the nucleon-nucleon interaction.

Although the nucleon number distribution is dramatically different from that given by Poisson statistics, when it is folded with the broad E_T distribution of proton-proton collisions there is only a small effect on the E_T distribution for proton-nucleus collisions. This work was reported at the "Physics at One Gigaflop" conference at Oak Ridge.

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f. Isospin-Invariance Breaking in the Two- and Three-Nucleon Systems
(W. Glöckle, T.-S. H. Lee and R. B. Wiringa)

We show that by combining the Paris potential and the existing charge-symmetry-breaking (CSB) and charge-independence-breaking (CIB) NN potentials, the nn and pp scattering lengths can be described very well within theoretical uncertainties. The calculated np scattering length is about 3 fm less than the data. A phenomenological model is then constructed to fit the np scattering length and is used in three-nucleon bound-state calculations. In a 5-channel Faddeev calculation in momentum space, the CSB and CIB effects in three-nucleon bound states are found to be 68 keV and 97 keV, respectively.

We find the effect of the observed charge-independence-breaking in $^1S_0$ nucleon-nucleon scattering on the binding energy of the triton to be of the order of 80 keV. When corrections for this effect are made in an 18-channel momentum-space Faddeev calculation, we find the Paris and Argonne v_{14} potentials give triton binding energies that differ by only 20 keV.

g. Charge-Symmetry Breaking ΛN Interaction (A. R. Bodmer)

From previous work on the mirror nuclei $_\Lambda{}^4$H, $_\Lambda{}^4$He, we established that the phenomenological charge-symmetry breaking interaction (the difference between the Λp and Λn interactions) is effectively spin independent. This is in striking disagreement with the existing predictions of meson-exchange models. We have been re-examining these models and also studying coupled-channel and many-body contributions to the charge-symmetry breaking to see whether conventional hadronic effects could account for the phenomenological interactions.

We are also studying quark structure contributions to the charge-symmetry breaking since these are strongly suggested as a major contribution in view of the failure so far of hadronic effects to account for the breaking.

h. The α-Cluster and Multi-Λ Hypernuclei (A. R. Bodmer and Q. N. Usmani*)

We are continuing variational calculations of $_\Lambda{}^9$Be with an α-cluster model, $2\alpha+\Lambda$, making better allowance for the angular momentum dependence of the $\alpha\alpha$ potential. In particular, 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 about 3 MeV, consistent with experiment, implying that the state is particle stable (with respect to breakup into $_\Lambda{}^5$He + α at a threshold 3.5 MeV above the ground state) and that it should decay by γ transition to the ground state.

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We are studying multi-Λ hypernuclei, in particular light nuclei with mass number A ≤ 6, containing two or more Λs. Such systems may become of experimental interest in the near future, and both their binding energies and decay properties are of interest. In particular, we intend to make Monte Carlo variational calculations in the framework of the phenomenological model of hypernuclear interactions which we have previously developed. Also of considerable interest are heavier multi-Λ hypernuclei, in particular (infinite) nuclear matter containing a finite fraction of Λs.

i. Deep-Inelastic Lepton Scattering by ^{3}He and ^{3}H
(F. Coester, U. Oelfke,* P. U. Sauer*)

Since accurate bound-state wave functions are available for ^{3}He and ^{3}H, these nuclei provide a good test case for the so-called "convolution model" of deep-inelastic lepton scattering by nuclei. Different convolution formulae have been derived in the literature under inequivalent physical assumptions. The purpose of this study is a critical quantitative comparison of the different assumptions and their consequences. We are also examining the relations to successful treatments of inelastic electron scattering by three-body nuclei at lower energies. We expect to finish a paper on this subject in the current year.

*University of Hannover, West Germany

j. The Spin Structure of the Proton (F. Coester)

Computing the spin structure function of the proton by nonrelativistic composition of the quark spin yields results in disagreement with recent experiments. The momentum-dependent Melosh rotations of the quark spins, required for a relativistic spin composition, result in a partial depolarization of the quarks which is highly sensitive to the transverse momentum distribution. We constructed a simple quark model to study this mechanism. It is possible to roughly fit both the empirical valence distributions and the spin structure function. However, the transverse momentum distributions required for this fit are unreasonable. For reasonable transverse momentum distributions the spin structure function is too small rather than too large. An adequate explanation of the data requires a more sophisticated model.

k. Light-Front Dynamics of Elastic Electron-Deuteron Scattering
(F. Coester and P. L. Chung)

Measurements of the deuteron form factors over a wide range of momentum transfer can provide important clues to the role of subnucleon degrees of freedom in nuclear dynamics. For a meaningful calculation of the form factors it is essential that the current density operators and the deuteron wave function transform under Lorentz transformations in a mutually consistent manner. We use standard nucleon-nucleon interactions to construct unitary representations of the Poincaré group on the two-nucleon Hilbert space. Deuteron wave functions represent eigenstates of the four-momentum operator. Existing parameterizations of measured single-nucleon form factors are used to construct a conserved covariant electromagnetic current operator. The light-front symmetry of the representation allows a clean separation of the effects of one- and two-body currents for arbitrary momentum transfers. Comparison with data indicates that for $Q^2<8$ GeV^2 the elastic cross sections are not dominated by two-body currents. A paper will be published in the proceedings of the International Conference on Medium- and High-Energy Physics, held in Taipei, Taiwan, 23-27 May 1988.

ℓ. Relativistic Corrections to the Magnetic and Quadrupole Moments of the Deuteron (P. L. Chung, F. Coester and B. D. Keister*)

We have calculated the quadrupole and magnetic moments of the deuteron assuming light-front dynamics. The advantage of this approach is that conventional bound-state wave functions and empirical nucleon form factors can be used to construct eigenfunctions of the four-momentum and the spin together with a representation of the electromagnetic current in such a way that the current-density operator and the wave functions transform consistently under a unitary representation of the Poincaré group. The sensitivity of our model to the choice of the deuteron bound-state wave functions is tested by using Reid Soft Core, Argonne v_{14}, Paris and Nijmegen nucleon-nucleon interactions, as well as three Bonn potentials. The exact results increase both quadrupole and magnetic moments by small amounts compared to the nonrelativistic values. Expansions in powers of the nucleon velocity are found to be unreliable. A paper has been submitted for publication.

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m. Electromagnetic Nucleon Form Factors (P. L. Chung and F. Coester)

We are calculating the charge and magnetic form factors of the proton and neutron for a relativistic quark model with structureless constituent quarks. The wave functions are spin-1/2 eigenfunctions of the four-momentum. Preliminary results indicate that for momentum transfers Q^2 less than 10 GeV^2 agreement with the available data can be achieved. As in the case of the pion we find that the confinement radius is substantially smaller than the charge radius. The relativistic composition of the quark spins is essential for the result.

n. Theory of High-Energy Electron Scattering by Composite Targets (F. Coester)

An invited lecture was presented at the International Spring School on "Medium- and High-Energy Nuclear Physics" held in Taipei, Taiwan, May 16-21, 1988. The emphasis in these expository lectures was on the role of relativistic invariance and the unity of the theory for medium and high energies. After an introduction of the kinematic notation and an elementary derivation of the general cross section, the relevant properties of the Poincaré group and the transformation properties of current operators and target states were described. Compatible representations of both current operators and target-state vectors with kinematic light-front symmetry were discussed. The distinction from the alternative Green's-function description was emphasized. The principal focus was on two applications: i) an impulse approximation for inclusive electron-nucleus scattering at both medium and high energies, and ii) the parton model of the proton applied to deep-inelastic scattering of polarized electrons by polarized protons. The lectures will be published in the proceedings.

o. Relativistic Models in Nuclear and Particle Physics (F. Coester)

An invited paper was presented at the International Workshop on "Nuclear and Particle Physics on the Light Cone" held at Los Alamos, July 18-22, 1988. The purpose of this talk was to give a comparative overview of different approaches to the construction of phenomenological dynamical models that respect basic principles of quantum theory and relativity. Wave functions defined as matrix elements of products of field operators on one hand, and wave functions that are defined as representatives of state vectors in model Hilbert spaces on the other, are related differently to observables. Dynamical models for these wave functions each have distinct advantages and disadvantages. Detailed presentations were given by subsequent speakers. The paper will be published in the proceedings of the Workshop.

B. INTERMEDIATE ENERGY PHYSICS

(C.-R. Chen, C. Fasano,* T.-S. H. Lee, and others)

The focus of our research has long been the development of a nuclear Hamiltonian for describing the excitation of the Δ resonance and the production/absorption of pions in nuclei. This is pursued by carrying out extensive studies of NN scattering up to 1-GeV laboratory energy. Starting with the meson theory of nuclear forces, we constructed such a model in the past few years. In 1988, we further demonstrated the success of that model by describing extensive new NN scattering data, and in the meantime also improved the model from the point of view of quantum chromodynamics. Guided by the quark-compound-bag model of the NN interaction, we constructed a new meson-exchange Hamiltonian with a separable parameteriza-tion of the short-range interaction. The model has resolved the long-standing problem of fitting the NN polarization data. This work will be the starting point for constructing a more realistic model by relating the short-range separable parameterization to basic QCD parameters.

In 1988 we succeeded in extending the meson-exchange nuclear Hamiltonian to include the electromagnetic production of pions and the Δ resonance. This was done by carrying out extensive studies of electromagnetic production of pions from the nucleon up to 500-MeV laboratory energy. We have used this model in an attempt to analyze the recent Argonne-Caltech data for deuteron photodisintegration; so far this data appears to be unexplainable by such a conventional meson-nucleon picture. The model has also been applied to electromagnetic production of pions from the deuteron and ^{3}He.

a. QCD-Inspired πNN Model Hamiltonian (C. Fasano* and T.-S. H. Lee)

For investigating nuclear reactions induced by intermediate- and high-energy probes, it is necessary to extend the conventional nuclear Hamiltonian to include pion and delta degrees of freedom. With the development of quantum chromodynamics (QCD) as the theory of strong interactions, an acceptable model should meet three theoretical requirements: (1) the long-range mesonic interactions should be related to the well-established Chiral dynamics; (2) the short-range part should be related to quark-gluon dynamics as described by various QCD-inspired models of hadron structure; (3) the theory should give an accurate description of all NN data up to about 1-GeV laboratory energy. We have succeeded in constructing such a model Hamiltonian. The basic NN and NΔ interactions of the model are: (1) the long-range part is calculated from one-pion and one-rho-exchange mechanisms of an effective Chiral Lagrangian; (2) the short-range part is parameterized in a separable form, as suggested by the quark-compound-bag model we have developed in the last two years to describe s-wave NN scattering up to 1 GeV. The model gives a very precise fit to the most recent Arndt phase-shifts. The calculated pp cross sections are in good agreement with extensive data. In particular the long-standing problem of describing the energy dependences of the $\Delta\sigma_L^{tot}$ and $\Delta\sigma_T^{tot}$ has been resolved. The work has been submitted by Fasano as his Ph.D thesis to the University of Chicago. The results have been reported at several conferences. A paper is being prepared for publication.

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b. Three-Nucleon Force in the Quark-Compound-Bag Model
(C. Fasano* and T.-S. H. Lee)

We have derived a model of the three-nucleon force from the one-pion-exchange interaction between nucleons and a six-quark bag excited during the NN collision at short distances. The parameters determining the excitation of the six-quark bag are taken from the quark-compound bag model of NN scattering up to 1 GeV. The pionic couplings with the bag states are deduced from the Cloudy Bag Model. Their effect on the binding energy of the three-nucleon system is calculated and found to be about -0.05 MeV. A paper reproting these results has been accepted for publication.

*Thesis Student, University of Chicago, Chicago, IL

c. Meson-Exchange Calculations of NN and πd Reactions
(T.-S. H. Lee and A. Matsuyama*)

To further explore the dynamical content of the meson-exchange πNN model we have constructed in the past few years, we have made comparisons of our predictions with extensive new np scattering data from LAMPF. It is found that the calculated differential cross sections and polarization parameters C_{SS}, C_{SL}, C_{LL} are in excellent agreement with the data. The results were reported in an invited talk at the workshop on Baryon-Baryon interactions held at Bad Honeff, June 1988. New experiments are also being planned by H. Spinka of Argonne to further test our predictions. The predicted $\pi d \to pp$ and $NN \to NN\pi$ cross sections, however, do not agree well with the data. This is consistent with several previous meson-exchange calculations. We have found that the problem is indeed due to the lack of a short-range NΔ interaction, as suggested recently by Farary et al. We are now exploring the possibility of resolving the problem by using the meson-exchange NΔ interactions deduced from a recently constructed QCD-inspired effective Chiral Lagrangian.

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d. <u>Photodisintegration of the Deuteron in the GeV Energy Region</u>
(T.-S. H. Lee)

The objective of this calculation is to examine whether the most recent d(γ,p)n data obtained by the Argonne-Caltech collaboration can be described within the conventional meson-exchange model. It is assumed that the mesons are first produced from the absorption of the incident photon by one of the nucleons in the deuteron, and then are subsequently absorbed by the second nucleon. The two outgoing nucleons interact with each other via the exchange of mesons, as described by our πNN model (see IV.B.c.). So far the calculation has been carried out by using a simple isobar model for producing the P_{33}(1236), P_{11}(1440) and D_{13}(1540) resonances. The calculated differential cross sections agree with the data below about 700 MeV, but are about a factor of three higher in the GeV energy region. Within the limitation of using three resonances, we have made many parameter variations and we conclude that a consistent description of this and other data is not possible in such a conventional meson-exchange model. This result was reported at the International Conference on Intermediate and High Energy Nuclear Physics held at Taiwan in May 1988, and was compared with a QCD prediction in a publication by Napolitano et al. We are now developing a new model which can account for all (~ 10) higher nucleon resonances. The computer program is being developed for this large-scale calculation, and we expect the results before the 1989 APS Spring meeting.

e. <u>Electromagnetic Production of Pions from the Nucleon</u>
(T.-S. H. Lee, B. Blankleider,* and S. Nozawa*)

The production of pions from the nucleon has been conventionally described by a Born term deduced from the Lagrangian field theory and a resonant term involving the excitations of nucleon resonances such as the Δ and N*(1470). An unsatisfactory aspect of all of the existing models is an on-shell approximation of the final πN interaction. Agreement with the data is usually achieved by introducing additional parameters and hence the validity of this conventional model is not fully established. To resolve this problem, we have carried out a study of the $\gamma N \rightarrow \pi N$ reaction with a unitary treatment of the πN final-state interaction. The calculation has been done

*PSI (Paul Sherr Institute), Villigen, Switzerland by using a final πN wave function generated by solving a relativistic three-dimensional Lippmann-Schwinger equation with a driving term deduced from the Cloudy Bag Model and fitted to the πN phase shifts up to about 1-GeV pion laboratory energy. In addition, we have constructed a gauge-invariant Born term which is consistent with our relativistic three-dimensional formulation of the πN problem. Our results show that the usual on-shell approximation is not valid in the Δ-resonance region. To determine the $\gamma N \to \Delta$ E1+ transition from the forthcoming $\gamma N \to \pi N$ data from Bates, it is essential to use a unitary approach as developed in this work. With appropriate electromagnetic form factors, it is shown that the model can describe the cross sections of the photoproduction of charged pions up to the Δ-resonance region. A paper describing our results is being prepared for publication. The model has been extended to describe the $e+N \to e'+N+\pi$ process.

f. Electromagnetic Production of Pions on the Deuteron (T.-S. H. Lee)

We have employed the unitary $\gamma N \to \pi N$ model described in IV.B.e. to calculate the $d(e,e'\pi)$ coincidence cross sections in the kinematic region where the final πNN interaction is small. The calculation has been performed by integrating the off-shell amplitude of the elementary $e+N \to e'+N+\pi$ process over the deuteron wave function. The calculated cross sections are in good agreement with the recent data obtained by the Saclay-Argonne collaboration. It is found that the Pauli principle plays an important role in understanding the ratio of the production cross sections from the nucleon and the deuteron. The calculated π^+/π^- ratio is also in fair agreement with the data. In an exploratory study based on the Cloudy Bag model of the nucleon, we show that the present data can be related to the pion distribution function of the nucleon. However a quantitative conclusion cannot be made unless the employed $\gamma N \to \pi N$ model is further improved to accurately fit the data and the final πNN interaction is taken into account.

g. Study of the Δ in Nuclei from the $^3He(e,e'\pi)$ Reaction
(T.-S. H. Lee)

The $d(e,e'\pi)$ program described in IV.B.f. has been extended to calculate quasi-free pion production from either a nucleon or a Δ in three-nucleon systems. The objective is to identify the kinematic region where the $^3He(e,e'\pi)$ coincidence cross section is most sensitive to the presence of the Δ component in three-nucleon systems. The pion production from the nucleon can be carried out straightforwardly by using the unitary $\gamma N \rightarrow \pi N$ model described in IV.B.e. The contribution from the Δ in ^3He is calculated from a $\gamma\Delta \rightarrow \Delta$ vertex normalized within the quark model to the experimentally determined $\gamma N \rightarrow \Delta$ vertex. The computer program has been developed and calculations are being performed to predict the effect of Δ component on the the π^+/π^- ratio, according to the suggestion by Lipkin and Lee.

h. A Microscopic Study of Δ Excitation in $^{12}C(e,e')$ Reaction
(C. R. Chen and T.-S. H. Lee)

Our primary interest is to examine the extent to which the inclusive $^{12}C(e,e')$ data in the GeV energy region can be understood from the elementary $\Delta \leftrightarrow \pi N$ and $N\Delta \leftrightarrow NN$ processes. We have shown that the main features of the Δ peaks can be described provided that: (a) the strength of the Δ excitation is adjusted to fit the total cross sections of the $\gamma N \rightarrow \pi N$ and $\gamma d \rightarrow np$ reactions, and (b) the medium effect on Δ propagation is described by an average Δ-nucleus potential deduced from the Δ-hole model of photonuclear reactions. The contribution from the $N\Delta \rightarrow NN$ two-body mechanism significantly improves the fit to the data in the "dip" region. The predicted magnitudes in the Δ region are about 20% lower than the data, indicating the importance of more complicated multinucleon processes. A paper describing our results has been published.

C. HEAVY-ION INTERACTIONS

(H. Esbensen, S. Landowne, S. Fricke, C. E. Price, and others)

Our heavy-ion studies concentrate on reactions near the Coulomb barrier and the application of coupled-channels techniques to these reactions. The channels considered consist of inelastic states of both the projectile and target and of channels in which a few nucleons are exchanged between the projectile and the target. Nuclear structure considerations are clearly important in choosing the channels to include, and we attempt to see the effects of nuclear structure on the measured cross sections. We are active both in developing new techniques for these calculations and applying them to experimental data.

These studies have led to a number of significant new results this year. We have studied collisions with heavy, deformed nuclei and applied the sudden limit of the so-called rotating-frame approximation to calculate the cross sections for two-neutron transfer reactions to specific final spin states. Such experiments are presently being performed at Oak Ridge. Our calculations have had a clear impact on the interpretation of the data. We have, in particular, studied the spin selectivity in pair-transfer reactions. This is a crucial question if one wants to use pair-transfer reactions as a spectroscopic tool.

We have also made significant progress in our ability to confront heavy-ion reaction data at energies near the Coulomb barrier. Our approach is to include the most dominant reaction channels and to calculate fusion, transfer, elastic and inelastic cross sections simultaneously in a coupled-channels treatment. This allows us to study the interplay between the different reaction channels. A particularly interesting issue that we have studied is the enhancement of subbarrier fusion cross sections due to the couplings to other reaction channels. We have also extracted and studied the local optical potential for elastic scattering that is generated by the couplings.

a. Two-Particle Transfer Reactions with Heavy Deformed Nuclei
(H. Esbensen, S. Landowne and C. E. Price)

We have completed a set of calculations for two-neutron transfer reactions in collisions between heavy and deformed nuclei. We have used Ni, Sn and Pb as projectiles and ^{162}Dy as a typical target and calculated the angular distributions for two-neutron pick-up reactions leading to different final spin states in ^{160}Dy. The calculations were performed in the sudden limit of the rotating-frame approximation, which makes the calculations physically transparent and very economical, whereas a full coupled-channels approach for such reactions would be extremely complicated and time consuming.

A characteristic feature of the results is a strong interference pattern in the angular distributions for two-neutron transfer reactions to low final-spin states. The interference pattern disappears at higher spins, where the angular distributions become bell-shaped. We have demonstrated that the structures at low spins are due to an interference of amplitudes that correspond to the scattering from different orientations of the deformed target. Such interference patterns have recently been observed at Oak Ridge for the reaction ^{162}Dy(^{116}Sn,^{118}Sn)^{160}Dy. Our calculations are in good agreement with the data. Our results have been published.

b. Angular Momentum Selectivity in Pair-transfer Reactions with Heavy Deformed Nuclei (H. Esbensen, S. Landowne and C. E. Price)

We are interested in exploring the possibility of using pair-transfer reactions to study nuclear structure phenomena at high spins in collisions between heavy and deformed nuclei. The problem is that a pair-transfer reaction to a specific final spin state probes several intermediate states from which the transfer can take place. Our calculations show that the transfer amplitude for a large final spin I is built from a constructive superposition of intermediate transitions centered about spin I/2. We have also derived this result analytically in the low-energy limit. The intermediate spin distribution is much broader for low final spins, and there is a strong interference and cancellation among the different amplitudes associated with the transfer from different intermediate states. This work has been published.

c. Pronounced Deformation Effects on Low-Energy Transfer Reactions
(S. Landowne and C. H. Dasso*)

Our recent studies of transfer reactions were carried out for systems where a heavy, spherical nucleus bombards a heavy, deformed target. By further extending our techniques it will be possible to calculate cases where the projectile is also a heavy, deformed nucleus. As a first step in this direction, we have used semi-classical approximations to derive estimates for cross section in such collisions at low bombarding energies. The results show a strong deformation effect on the transfer cross section. This work has been published.

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d. Transfer Reactions in the Sudden Limit of the Pairing-Rotor Model
(S. Landowne, C. H. Dasso,* and G. Pollarolo†)

There have been many speculations about the possibility of observing correlated multi-particle transfer processes in heavy-ion collisions. A novel approach to such problems that has been proposed recently is based on a macroscopic point of view. This model allows for the possibility of multi-pair transfer reactions in collisions which involve good pairing rotors. Here the transfer of pairs is related to rotations in an abstract gauge space. By analyzing this problem in the sudden limit, we are able to explicitly exhibit the prediction that the direct transfer of four particles dominates over the sequential pair-transfer at low energies. This work has been published.

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e. Coupled-Channels Calculations of Heavy-Ion Reactions Near the Coulomb Barrier (H. Esbensen)

I have summarized the status of coupled-channels calculations for heavy-ion reactions near the Coulomb barrier. Earlier calculations have focused on a limited set of reaction channels, and the absorption of flux into other channels, which have not been included explicitly, has been simulated by introducing an adjustable imaginary potential. In recent years most of the dominant reaction channels have been measured for several projectile-target combinations. This calls for more complete calculations, which include the most dominant reaction channels and avoid introducing imaginary optical potentials. The results of such an approach were illustrated for the reactions O+Pb and Ni+Ni. The summary was presented at the "Winter Workshop on Nuclear Dynamics V" in Sun Valley, Idaho, February 1988, and is published in the proceedings from the meeting.

f. Coupled-Channels Calculations for Transfer Reactions (H. Esbensen, S. Landowne and S. Fricke)

We have studied the effect of couplings to one-nucleon transfer channels on fusion and elastic scattering in a coupled-channels treatment. We have, in particular, investigated the rotating-frame approximation and derived a simple expression for its validity. The advantage of this approximation is that it makes realistic calculations feasible by considerably reducing the effective number of coupled channels.

We have applied the rotating-frame approximation in calculations of the reaction $^{58}Ni+^{64}Ni$ at energies near the Coulomb barrier. We have found that it is quite accurate for the most dominant one-neutron transfer channels. Including these channels, and the one- and two-phonon excitations of the low-lying 2^+ and 3^- states, we obtain a good agreement with the measured elastic scattering data. Furthermore, by including successive one-neutron transfers we obtain a reasonable fit to the measured one-neutron transfer cross sections.

The most dominant effect on the enhancement of the subbarrier fusion cross section arises, in these calculations, from couplings to the surface modes, whereas the one-nucleon transfer couplings have a smaller effect. There is still some discrepancy between the calculated and the measured fusion cross section. We expect that some of this discrepancy can be eliminated by including the couplings to direct two-nucleon transfers. In order to test this interpretation one would need more detailed measurements of two-particle transfer reactions. This work has been accepted for publication.

The low-energy fusion cross sections for $^{40}Ca+^{40}Ca$, $^{40}Ca+^{44}Ca$ and $^{40}Ca+^{48}Ca$ show variations which are not accounted for by couplings to inelastic excitation channels. We have made a number of calculations to ascertain the most important transfer reaction channels. We intend to calculate the combined effect of particle transfer reactions and inelastic excitations on the fusion of these systems. In particular, the favorable Q-values for charged-particle transfers may play a special role for the case $^{40}Ca+^{48}Ca$, which has the largest subbarrier fusion cross section.

g. Contribution of Nucleon Transfer to the Elastic Scattering of $^{28}Si+^{58,64}Ni$ Near the Coulomb Barrier (S. Landowne, Y. Sugiyama,* and others)

Last year we published a systematic analysis of the low-energy $^{28,30}Si+^{58,62,64}Ni$ fusion reactions measured at Legnaro. It was concluded that the observed variations in the fusion cross sections of $^{28}Si+^{58,64}Ni$ have now been measured in the energy range E_{cm}=50.-76.5 MeV, which extends below the Coulomb barrier. The transfer cross section of $^{28}Si+^{64}Ni$ is an order-of-magnitude larger than that of $^{28}Si+^{58}Ni$. The coupling effect of the transfer channel is clearly observed in the elastic scattering of $^{28}Si+^{64}Ni$, while the effect is small in $^{28}Si+^{58}Ni$.

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h. Coupled-Channels Calculations for Reactions with ^{16}O Beams
(H. Esbensen and F. Videbaek)

Systematic coupled-channels calculations for a series of heavy-ion reactions that employ ^{16}O beams have been performed. Previous analyses of the data were based on DWBA calculations, using an adjustable, energy-dependent optical potential. This approach is to include the most dominant reaction channels explicitly, using only a real, energy-independent nuclear potential. The fusion process is simulated by ingoing wave boundary conditions in all channels at a distance that is inside the Coulomb barrier.

Some reactions, as for example $^{16}O+^{58}Ni$ and $^{16}O+^{88}Sr$, are particularly simple, since transfer channels are suppressed by unfavorable Q-values. In these cases one can account quite accurately for the measured elastic and inelastic scattering data near the Coulomb barrier by including only the 2^+ and 3^- states in both projectile and target (see Fig. IV-2). At higher energies (twice the Coulomb barrier and higher) it becomes necessary to include more channels in order to account for the data. For other reactions, like $^{16}O+^{208}Pb$, it is necessary to include various transfer channels even near the Coulomb barrier, in order to explain the measured fusion, elastic and inelastic scattering data. This work is being prepared for publication.

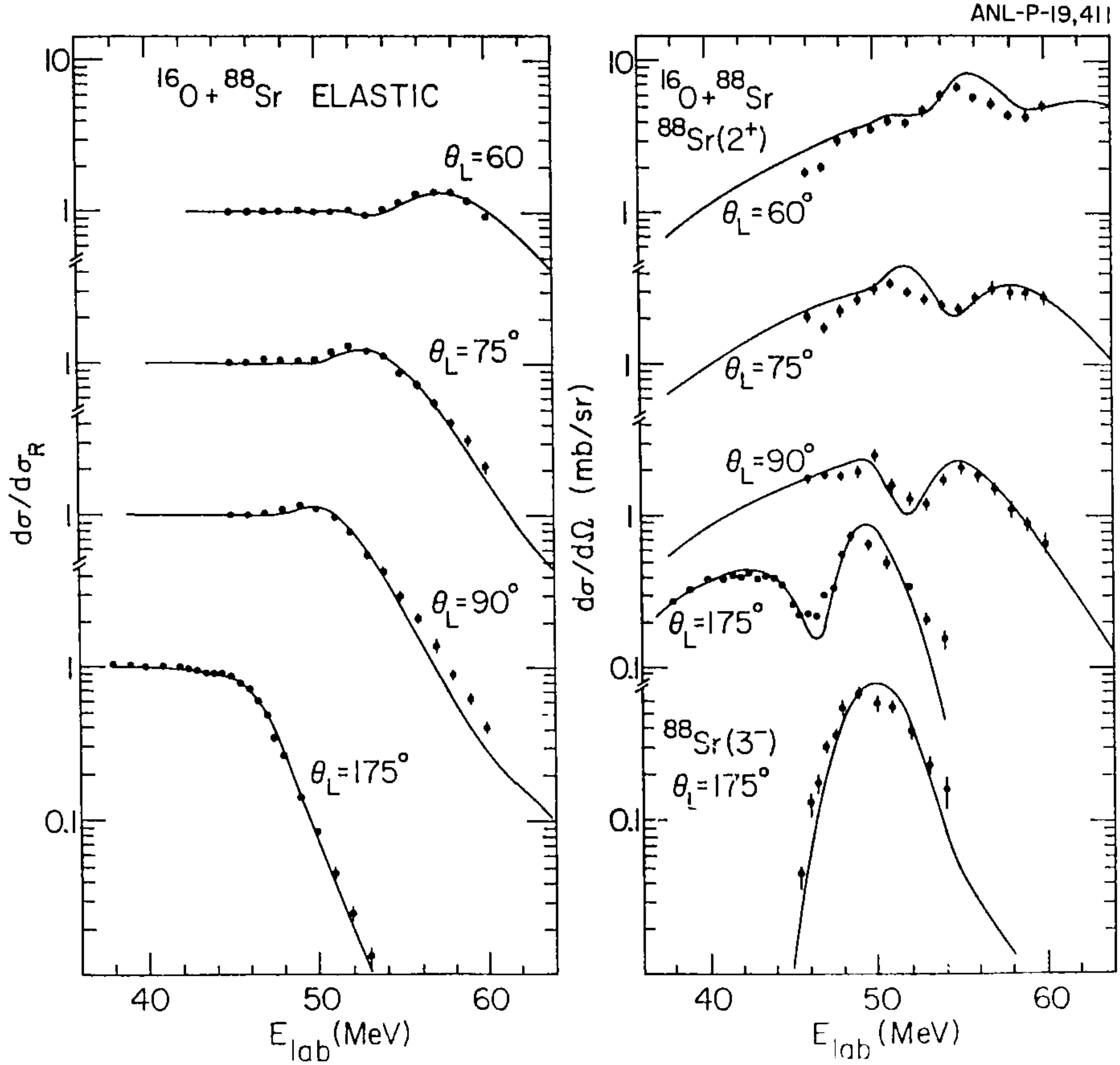

Fig. IV-2. Energy dependence of the differential cross section for elastic scattering of ^{16}O on ^{88}Sr and for the inelastic excitation of the 2^+ state at 1.836 MeV in ^{88}Sr, at four different scattering angles. Also shown are the cross sections for the excitation of the 3^- state at 2.73 MeV in ^{88}Sr at 175 degrees scattering. The curves show the results of coupled channels calculations which include the low-lying 2^+ and 3^- states in both projectile and target. The data are from P. R. Christensen et al., Nucl. Phys. A207, 433 (1973).

i. Dispersion Relation for Coupled, Closed and Open Channels
(H. Esbensen, S. Landowne, M. S. Hussein,* and others)

One of the interesting phenomena observed recently in heavy-ion collisions is an apparent dispersion relation satisfied by the optical potential. This is evidenced by an increase in the strength of the real potential as the energy is lowered toward the Coulomb barrier, while the imaginary potential decreases. Such a behavior can be explained qualitatively on general grounds using the Feshbach formalism based on couplings to open reaction channels. However, a unique feature of the coupled-channels model we have developed is the simulation of the fusion process by ingoing wave boundary conditions. This introduces a loss of flux which corresponds to having closed channels. Consequently, one expects to have a more general type of relation between the real and imaginary parts of the effective optical potential. We are currently investigating this problem.

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j. Comment on Energy-Dependent Barriers for Heavy-Ion Fusion
(S. Landowne, C. H. Dasso,* and G. Pollarolo†)

The observation that the real part of the optical potential for elastic scattering increases in strength near the Coulomb barrier has led to proposals for using energy-dependent potential barriers to describe heavy-ion fusion reactions. Already a number of studies have tried to establish a correlation between the enhancement of the low-energy fusion cross section with an increase in the real part of the elastic-scattering optical potential. We point out that such a direct correlation is highly oversimplified in that it fails to account for the energy dependence of the compound-nucleus spin distribution.

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D. NUCLEAR STRUCTURE STUDIES

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

The goal of this program is to understand the strong correlations in nuclear states that are due to the effective two-body interaction. These effects are manifest in strongly deformed nuclides and can be well treated in such cases through the introduction of deformation into the single-particle potential. In transitional nuclides, however, such an approach is not adequate for obtaining a reasonable description of nuclear states. It is a major challenge of nuclear structure theory to devise methods of treating states that are weakly deformed, or very soft vibrators. In our studies, we utilize both the deformed single-particle potential methods and true many-body wave functions to understand nuclear properties. Our major interests include: (1) the study of octupole correlations and the correlations due to higher multipoles in the heavy elements; (2) the study of the changes in nuclear shapes as a function of angular momentum in the rare-earth and heavier mass nuclides; this includes both the gradual change from spherical to slightly oblate shapes along the yrast line and the possible superdeformed nuclear states in these nuclides; (3) developing new many-body methods for dealing with weakly-deformed nuclear states; (4) the study of the competition and coexistence of collective modes at low and moderate excitation energies. This research involves a strong collaboration with the experimental programs at Argonne.

A major effort in the past year has been a series of calculations on superdeformation at high and low angular momentum. Until now, the only high-spin superdeformed nuclides that have been studied are nuclides near ^{150}Gd. Calculations that we have recently completed using the cranked Strutinsky method suggest that there is an extensive new region of superdeformed nuclides near A~200 that are accessible with heavy-ion reactions at the ATLAS facility. An experimental search is being carried out for these superdeformed nuclides by R. Janssens and collaborators at Argonne. We are also doing calculations involving superdeformed nuclides in the A~150 mass region in conjunction with the experimental program at Argonne.

We have made considerable progress in this past year on a many-body code for dealing with many coexisting residual interaction modes. The efficiency of our code has been improved to the point that we are able to carry out detailed calculations of residual interaction effects in several nuclides to get some idea of the role of particular multipoles in determining the structure of low-lying nuclear states. We have studied the role of 2^5-pole interactions in determining the reflection asymmetric features of nuclides in the light actinides and find the rather interesting result that the correlation energy associated with the 2^5 multipole varies in a manner that is quite different from the behavior of the octupole mode in these same nuclides.

Both the calculations involving many-body wave functions and those involving superdeformation require large amounts of supercomputer time.

We have continued our studies of p-shell nuclei by examining the suppression of certain transitions in A = 13 and A = 14 nuclei at large momentum transfer. Although different contributions dominate, a suppression consistent with that at lower momenta is found.

a. A New Region of Superdeformation in Nuclides (R. R. Chasman)

We have carried out an extensive series of calculations using the cranked Strutinsky formalism to explore the nuclides near A = 190 for possible cases of superdeformation. The single-particle potential that we use is of the Woods-Saxon form, with the potential parameters determined from an analysis of high-spin excited states in the ^{146}Gd region using many-body wave functions. These calculations show a new extensive region of superdeformed nuclides in the Os-Ir-Pt-Au-Hg isotopes with neutron numbers between 110 and 120 that have deformations of $\beta_2 \sim 0.55$. Many of these superdeformed states should be accessible in heavy-ion reactions, because the superdeformed shape is calculated to be lowest in energy at angular momenta below I = 50 in most of these nuclides (see Figs. IV-3 and IV-4). We note that the superdeformed potential well depth is even larger in this region than in the ^{152}Dy region. In contrast to the ^{152}Dy region, the superdeformed minimum is expected to persist down to I = 0 in the Hg region. This should allow us to gain detailed information about nuclear structure at large deformation. This study has been accepted for publication.

We have also found a few nuclides near ^{204}Rn that are expected to be superdeformed, with deformations of $\beta_2 = 0.65$. These nuclides should be somewhat more difficult to produce than those in the Hg region because of increased fission competition and because the superdeformed shape is slightly higher in energy relative to the ground state. The depth of the superdeformed well is rather large in this region also.

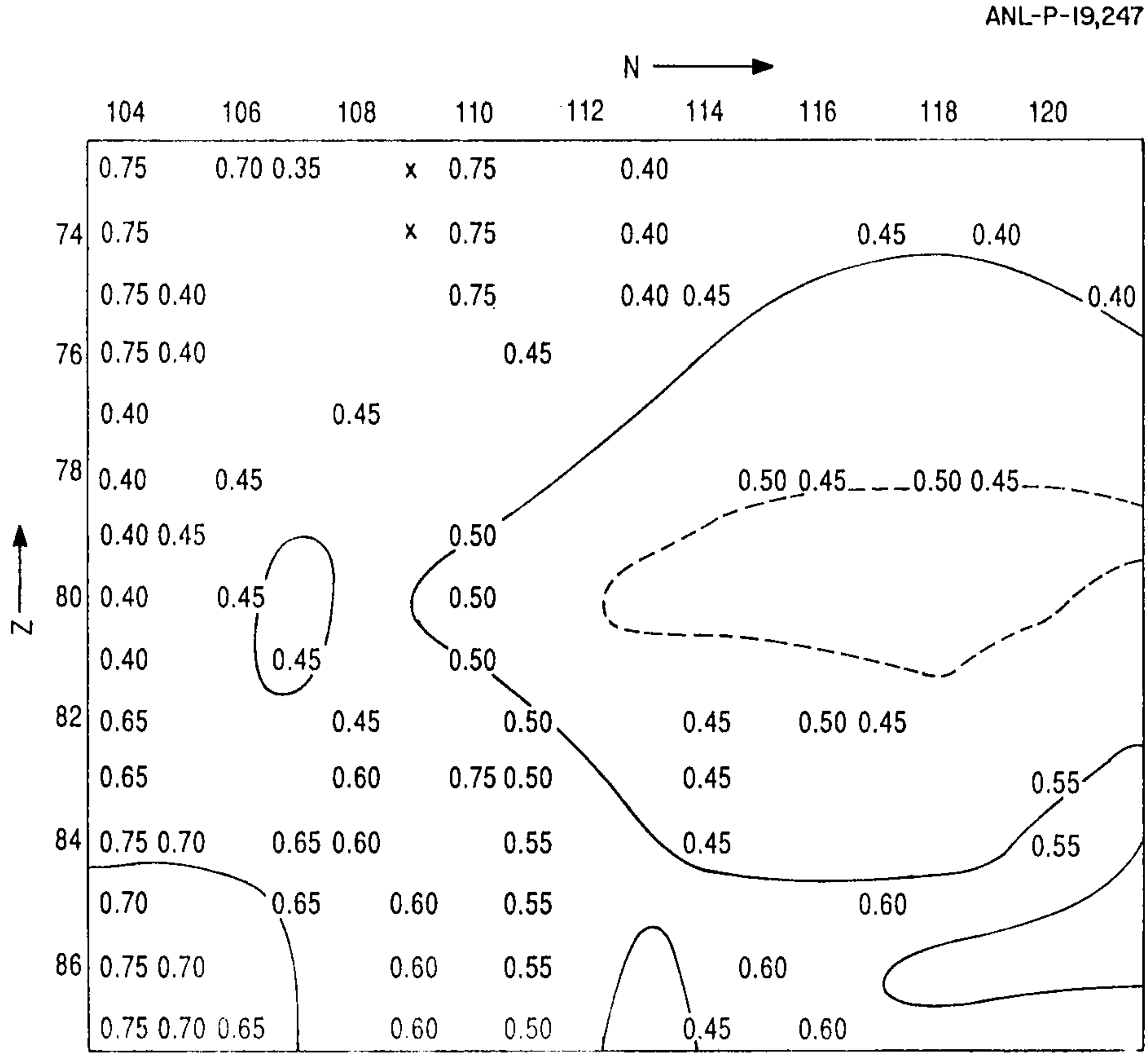

Fig. IV-3. Depth of the superdeformed minimum for nuclides near A=190, at I=40. Contours are shown for well depths of 3.5 and 2 MeV. The continuous line is the 2-MeV contour; the dashed line is the 3.5-MeV contour. The numbers inside the figure are quadrupole deformation parameters ν_2 of the superdeformed minimum. In each row, (i.e. for each value of Z) all nuclides to the right of a written value of ν^2 have the same value of ν_2.

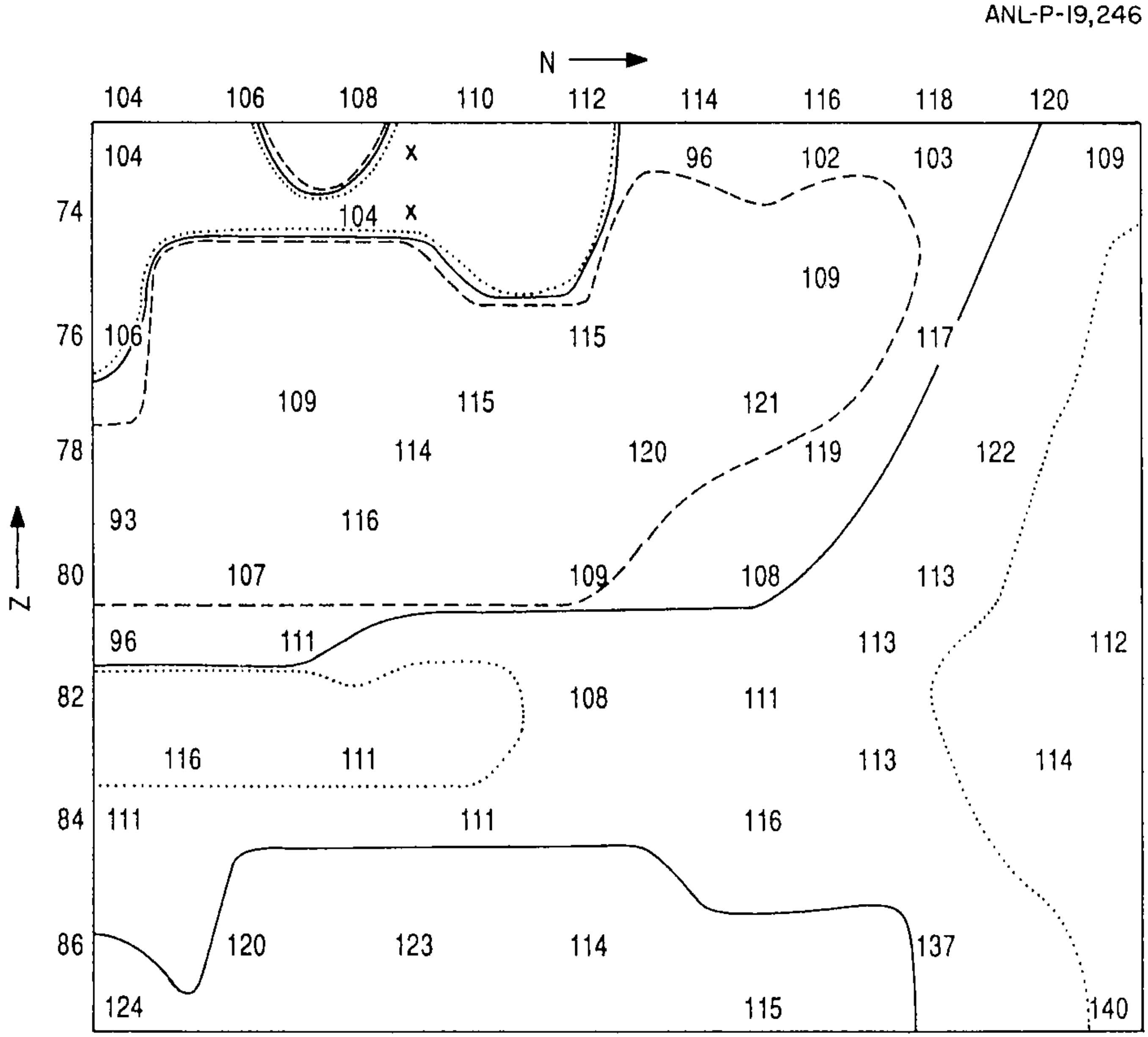

Fig. IV-4. Excitation energy of superdeformed state relative to lowest state at I=40. Contours are shown for 0.5 MeV (dashed), 2 MeV (continuous), and 4.5 MeV (dotted). The numbers inside this figure are the values of the moment of inertia for the superdeformed bands in selected nuclides.

b. Many-Body Wave Functions (R. R. Chasman)

A large part of our time this past year has gone into improving a code that we are developing for the study of many-body correlations in nuclei. In the approach that we are developing for axially symmetric quantum systems, the complexity of the calculation depends essentially on the number of levels having a given value of the projection of the angular momentum (J_z) on the symmetry axis of the system. The complexity of the calculation is relatively independent of the number of particles that are included. With the improvements that we have made in the code in the past year, it is now feasible to include up to seven levels of each value of J_z in our calculations. We can include many particle-hole or particle-particle multipole modes in the calculation.

c. Odd Multipole Correlations in the Light Actinides (R. R. Chasman)

We have applied our new many-body code to an investigation of odd-multipole correlations in the light actinide region. In this mass region, one finds extremely low-lying $K = 0^-$ rotational bands that signal the importance of negative-parity particle-hole correlations. In this research program, we have predicted the existence of parity doublets in the odd-mass nuclides of this region before their discovery, using a many-body treatment of octupole correlations. With the development of our new many-body code that can accommodate more levels, it is meaningful to consider the role of correlations coming from higher negative parity multipoles in these nuclides. We have studied the role of the 2^5 multipole in some detail. We find that it contributes 0.9 MeV of correlation energy in the $K = 0^-$ band of ^{234}U and 1.7 MeV of correlation energy in ^{224}Th. This increase is in marked contrast to the relative constancy of octupole correlation energy that we calculate to be 4.8 MeV in the $K = 0^-$ band of ^{234}U and 4.9 MeV in ^{224}Th. In our new calculations, we find that the odd multipole correlation energies in the $K = 0^+$ ground-state band are substantially less than in the $K = 0^-$ band, even in ^{224}Th where the $K = 0^-$ band is at 246-keV excitation energy. In the $K = 0^+$ ground state band of this nuclide, the octupole correlation energy is 3.2 MeV and the 2^5-pole correlation energy is 1.2 MeV. The large differences in correlation energy between the lowest 0^+ and 0^- bands show that the limit of

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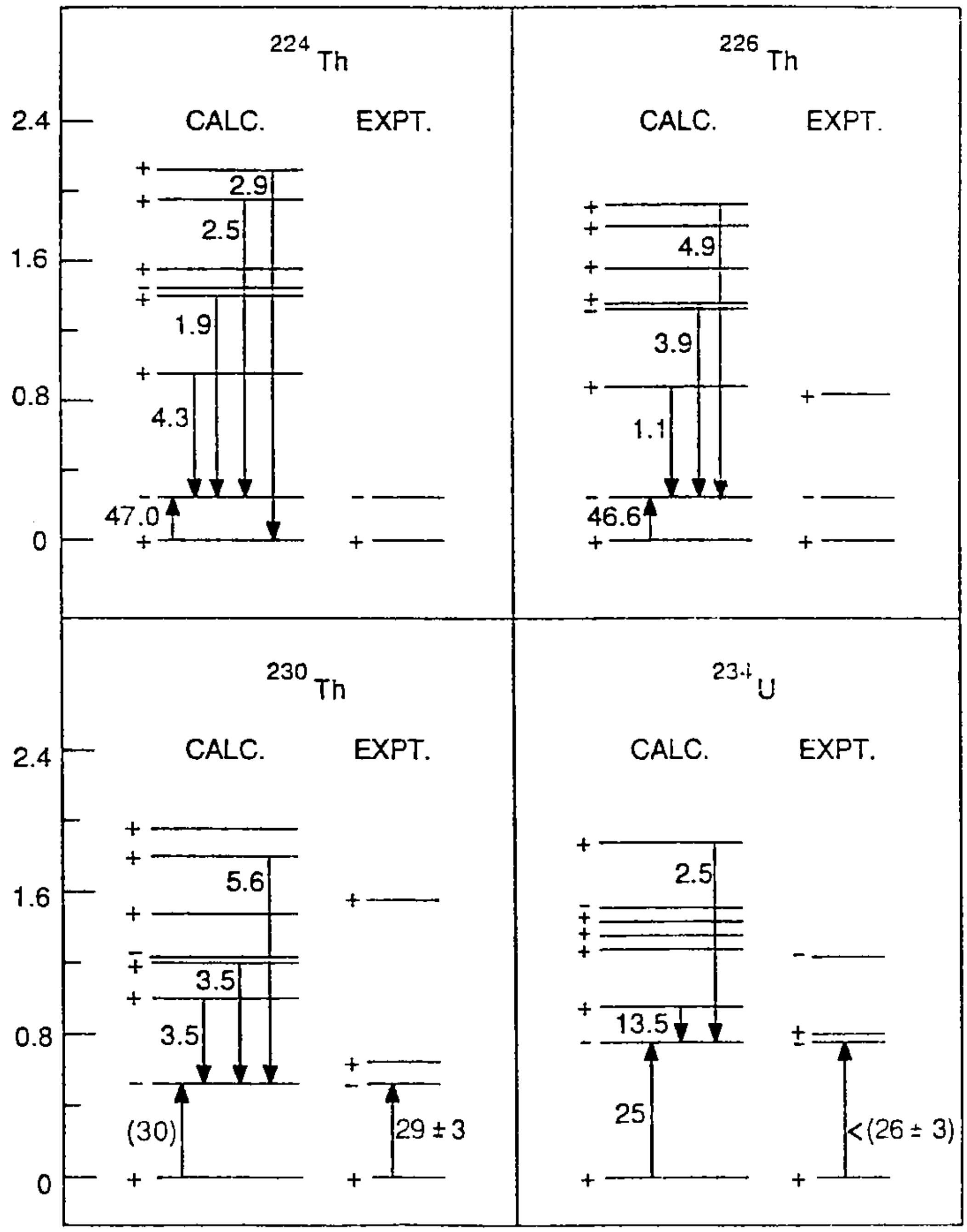

Fig. IV-5. Comparison of calculated and experimentally observed 0^+ and 1^- levels. + beside a level indicates 0^+ and - indicates 1^-. The numbers beside the arrows are B(E3) values. All B(E3) values are from the 0^+ state to the 1^- state.

octupole deformation is not attained in the even nuclides of this mass region. We also calculate E3 transition matrix elements. We find that in addition to the strong E3 transition moment between the ground-state band and the lowest $K = 0^-$ band there are several excited 0^+ bands that have appreciable E3 transition strength to the lowest 0^- band in the nuclides of this mass region (see Fig. IV-5). This includes the first excited 0^+ band where the transition energy is low and hard to observe and transitions from more highly excited 0^+ bands where the E3 transition energy is ~1 MeV and the transition might be measurable. This study will be published.

d. Search for Superdeformation in the Hg Region (R. R. Chasman, R. V. F. Janssens, E. F. Moore, I. Ahmad, T. L. Khoo, F. L. H. Wolfs, D. Ye,* K. Beard,* U. Garg,* Z. W. Grabowski,† and M. W. Drigert‡)

Our recent calculations have shown a large new region of superdeformed nuclides centered at ^{196}Hg. The calculations show that the superdeformed minimum is quite deep down to spins of I = 0 and it becomes yrast at relatively low spins. We find that the superdeformed shape becomes yrast at lower angular momentum when the neutron number is lowered. As fission competition is much more important in the Hg region compared to the Dy region, it is appropriate to study isotopes with relatively low neutron numbers where the superdeformed minimum is populated at lower angular momentum.

A bombardment of ^{160}Gd, with ^{36}S beams has been carried out at the ATLAS facility. This produces the nuclides ^{190}Hg and ^{191}Hg. A preliminary analysis of the gamma rays found in this study shows two superdeformed bands, having dynamic moments of inertia of 110 $\hbar$ $(MeV)^{-1}$. The stronger of the bands is assigned to ^{191}Hg and the weaker band is tentatively assigned to ^{190}Hg. The measured moments of inertia agree almost perfectly with the values obtained in the calculations; 110 $\hbar$ $(MeV)^{-1}$ for ^{190}Hg and 111 $\hbar$ $(Mev)^{-1}$ for ^{191}Hg.

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Because the superdeformed minimum is deep even at I = 0, the superdeformed bands in the Hg isotopes go to low spins. This feature may allow us to fix the Ω quantum numbers of the single-particle states in the superdeformed well. This will provide a strong constraint on single-particle potential parameters.

e. Superdeformation in ^{144}Gd and ^{143}Eu (R. R. Chasman, R. V. F. Janssens, E. F. Moore, T. L. Khoo, I. Ahmad, K. Beard,* D. Ye,* P. Benet,† Z. Grabowski,† and P. J. Daly†)

Although ^{144}Gd and ^{143}Eu are fairly close in mass to the known high-spin superdeformed nuclides near ^{152}Dy, the calculated superdeformation in these nuclides is caused by entirely different features of the neutron single-particle spectrum. Our calculations suggest that the superdeformation in these nuclides, particularly in ^{143}Eu, will persist down to low spin. Even when pairing effects are taken into account, the superdeformed well in ^{143}Eu is calculated to have a depth of ~1 MeV at I = 0. By studying these nuclides we hope to learn about nuclear structure at large deformation in detail in this mass region. An observation of the transitions between the superdeformed states and the ground state would provide a stringent test of the potentials used describing the nuclides of this mass region. We note that one does not have such information about any of the superdeformed nuclides near ^{152}Dy. A series of experiments is being planned to study these nuclides.

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f. Superdeformation in ^{151}Dy (R. R. Chasman, G. E. Rathke, R. V. F. Janssens, I. Ahmad, M. Hass, T. L. Khoo, H.-J. Körner, W. C. Ma, F. L. H. Wolfs, M. W. Drigert,* K. Beard,† U. Garg,† S. Pilotte,‡ and P. Taras‡)

Using the cranked Strutinsky method, one can calculate moments of inertia for superdeformed bands as a function of angular momentum. A prediction of the moment of inertia is particularly useful in experimental searches for superdeformation. We have carried out a calculation of the moments of inertia for superdeformed nuclides in the ^{152}Dy region. This has been used in a successful search for the gamma-ray transitions connecting the superdeformed levels of ^{151}Dy. We note that our calculated value agrees quite well with the measurement and proved quite useful in the discovery of superdeformation in this nuclide. The results of this study have recently been published.

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g. Assessment of the 1p-Shell Model for A=13,14 Nuclei (D. Kurath, K. Amos,* L. Berge,* and D. Koetsier*)

An analysis was carried out of information from β and γ decays as well as of extensive cross-section data from (e,e') and intermediate energy (p,p') and (p,n) reactions for select transitions in A = 13 and A = 14 nuclei. The forward-angle (p,n) cross sections and the β and M1-γ data require suppression of the calculated values, all resulting from the transition density multipole, J(LS) = 1(01). The purpose of the present analysis is to see whether reaction data at higher momentum transfer is consistent with this suppression and to consider the contributions of other multipoles with the same value of J.

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At higher momentum transfer, $q \sim 1$ to $2\ fm^{-1}$, the $J = 1$ contribution is dominated by the $J(LS) = 1(21)$ multipole. We find that the calculated results for this multipole are also too large compared to observations, indicating an appreciable suppression factor. The origin of this suppression for $A = 13$, 14 nuclei is understood as due to quadrupole deformation, and its magnitude can be estimated by means of a Nilsson model which includes $2\hbar\omega$ admixtures. Since the 1(21) and 1(01) contributions add as amplitudes it is important to account for the 1(21) suppression before evaluating the 1(01) contribution at lower q. A reasonably consistent picture is found for these nuclei.

E. RELATIVISTIC MEAN-FIELD THEORY OF NUCLEI

(A. R. Bodmer, F. Coester, C. E. Price, and others)

Many researchers have applied relativistic mean-field theories (RMFT) containing both scalar and vector potentials to nuclear structure and nucleon-nucleus scattering. We have investigated the conditions necessary to avoid pathologies that often arise in such theories at higher energies. We have also shown that a fully self-consistent calculation using RMFT of odd-mass nuclei gives good values for the magnetic moments of these nuclei; this had been an outstanding problem for earlier, less complete, calculations. We have also successfully applied RMFT to light unstable nuclei. Finally, we have studied the extent to which the successes of RMFT imply the correctness of their basic assumptions.

a. Phenomenology of Relativistic Mean-Field Theory of Nuclei
(A. R. Bodmer and C. E. Price)

Relativistic mean-field theories (RMFT) of nuclei involving scalar and vector fields have been extensively studied for more than a decade. The simplest (Walecka) version has only a linear coupling of the scalar field with the scalar nucleon density and has no scalar field self-interactions. However, more recent studies have shown conclusively that only with scalar self-interactions, in particular cubic plus quartic self-interactions (first considered by Boguta and Bodmer in order to give the theory additional flexibility needed for an adequate description of the nuclear surface and of the incompressibility coefficient K), does one obtain a simple and quite successful phenomenology of nuclei, both spherical and deformed, involving rather few parameters. However, the satisfactory phenomenological fits involve a negative quartic term which is phenomenologically acceptable only for positive energies. In applications to high-energy nuclear collisions, such a negative term may drive the scalar potential to unlimited negative and hence unphysical values, and can also lead to unpleasant and undesired additional solutions - "pathologies" of the theory.

We have studied RMFT with scalar self-interactions involving general scalar potential functions with a minimum at zero scalar field. The cubic-plus-quartic model is discussed as an important special case. We obtain quite general conditions on the scalar potential function required by the properties of nuclear matter at saturation, including the incompressibility coefficient K. These conditions depend only on K and the effective mass M^*. This plays a central role and is uniquely related to the coupling of the vector field to the nucleons. The causes of the pathologies of the theory are identified and a form of scalar potential function is suggested which provides a cure for the cubic-plus-quartic theory with negative quartic term, but which should preserve all its desirable features for finite nuclei. The equation of state (EOS) at $T = 0$ is discussed for a general potential U. We argue that the EOS is independent of the functional form of U so long as the parameters are adjusted to give the same K and M^*. In particular, a "healthy" U will give the same EOS as the cubic-plus-quartic model but without the problems of the latter.

The phenomenology of RMFT for finite nuclei is reviewed and discussed; we emphasize especially that the spin-orbit splitting in light nuclei determines M^* within quite narrow limits to be $\simeq 0.6$ M. The resulting EOS is then also effectively determined within narrow limits, quite independently of the functional form of U, and, as is well known, is quite stiff with little dependence on K. To model a softer EOS (e.g. into collision dynamics in order to compare with data and to learn about the EOS) requires further modifications of the theory. This work is being prepared for publication.

b. Systematics of Odd-Mass Nuclei in Relativistic Mean-Field Models
(C. E. Price and R. J. Furnstah*)

Relativistic mean-field models have been successfully used to provide descriptions of spherical nuclei and even-even, deformed nuclei using parameters that were adjusted to reproduce the bulk properties of nuclear matter. However, one of the early failures of these models was their inability to correctly predict the magnetic moments of nuclei that are one particle or hole away from a closed shell. In these calculations the closed-shell core was treated self-consistently, but the valence particle or hole was not and the entire moment came from this valence nucleon (extreme single-particle model). Subsequent calculations using the random phase approximation (RPA) to partially restore the self-consistency have shown that the failure to predict the magnetic moments was due to the inadequacy of the single-particle approximation and not due to any fundamental flaw in the relativistic mean-field model. In this work, we have carried out a fully self-consistent calculation for a variety of open-shell nuclei and have demonstrated that the relativistic model provides a good description of the magnetic moments, in agreement with the RPA results. We have also investigated the systematics of the binding energies, rms radii, quadrupole moments, nuclear currents and electromagnetic form factors, and have found that the quantitative agreement with experiment is equal to that which was found using non-relativistic Skyrme models. The one notable exception is that the predicted electromagnetic form factors are somewhat too large. We believe that this is an indication of the importance of properly including vacuum fluctuation corrections.

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c. Relativistic Mean-Field Calculations for Light Unstable Nuclei
(C. E. Price and J. Boguta*)

The effectiveness of relativistic mean-field models for describing the charge radii of light unstable nuclei has been investigated. Recently, secondary beam experiments have been used to measure the scattering cross sections for a variety of nuclei in the mass region A = 6-13; and, from these results, the root mean-square charge radii of these nuclei have been deduced. In this work, we have attempted to reproduce these results using a relativistic sigma-omega model in the Hartree approximation for finite nuclei. The model includes the non-linear self interactions of the scalar meson field and we have chosen to adjust the model parameters to reproduce the known rms radius of carbon-12. We have found that, with a few important exceptions, the relativistic model successfully predicts the trends in the radii for these light nuclei. The major exception is that the least stable nuclei (e.g. ^{11}Li) have much larger experimental radii than predicted in this model.

Since these nuclei are expected to be the most sensitive to small changes in the model, it is possible that the predictions could be improved by a slight readjustment of the parameters or by including higher-order effects (e.g. vacuum fluctuation corrections).

*Advanced Nuclear Concepts, San Fransisco, CA

d. Quantum-Field Theory of Nuclear Dynamics (F. Coester)

The successes of Dirac-spinor wave functions in describing nuclear properties and nucleon-nucleus scattering do not necessarily imply the validity of renormalizable Lagrangian field equations. They can be understood in terms of general properties of Green's functions and covariant vertex functions that are defined as matrix elements of renormalized Heisenberg fields between physical eigenstates of the four-momentum. Cluster properties of the many-body Green's functions provide, in principle, a relation between the two-nucleon problem and the many-body problem. This relation needs to be explored further. An invited paper was presented at the Workshop on Relativistic Nuclear Many-Body Physics, at Ohio State University, June 6-9, 1988.

F. QUANTUM MECHANICS WITH MAGNETIC CHARGES OR FLUX LINES (M. Peshkin)

In this project, fundamental questions in quantum mechanics are investigated that relate to magnetic charges and flux lines, and to physical systems confined to multiply connected regions of space. Past results for magnetic charges include the most general derivation of the Dirac quantization law and an analysis of the properties of the electromagnetic fields when both kinds of charges are present, including the identification of singularites which imply very general constraints on theories including magnetic charges. Past results for electrons interacting with flux lines (Aharonov-Bohm effect) include identification of the role of quantized angular momentum, removal of ambiguities due to the return flux problem, introduction of the bound-state Aharonov-Bohm effect, and an analysis of the general constraints on theories involving hypothetical cyons, structures composed of an electron bound to a flux line that may exhibit unusual spins and statistics. Recent results include a "toy" model in which the Dirac charge quantization appears as the quantization of a dynamical variable rather than as a constraint on the external electric and magnetic charges on the particles, an analysis of the electron holography experiments which shows that they are the first experiments to test the use of single-valued wave functions in a multiply-connected region, and an analysis of the consequences of Aharonov-Bohm effect for locality and causality in quantum mechanics.

a. Magnetic Dipoles and Electric Charge Lines (M. Peshkin)

A new kind of conceptual experiment in a multiply-connected space has been suggested, originally by Aharonov and Casher. Here a neutron (magnetic dipole) is scattered by an electrically-charged thread and phenomena similar to Aharonov-Bohm effect are predicted by the theory. These phenomena are partially obscured by questions relating to classical motion in such a configuration. A simple classical analysis has been found which apparently avoids previously debated questions about the representation of a neutron in classical theory. Its consequences are being investigated.

b. Lessons Learned From the Aharonov-Bohm Effect (M. Peshkin)

With A. Tonomura (Hitachi Advanced Research Laboratory), I am preparing a monograph on the Aharonov-Bohm effect. My part consists of a review of the theory as constrained by the experiments and an analysis of what the experiments teach us about fundamental questions in quantum mechanics. Publication is expected in 1989.

ATOMIC AND MOLECULAR PHYSICS

Atomic Physics research in the Physics Division consists of four principal ongoing programs:

(1) High-resolution laser-rf spectroscopy with beams of atoms and molecules (W. J. Childs),

(2) Fast ion-beam/laser studies of atomic and molecular structure (L. Young, H. G. Berry and W. J. Childs),

(3) Interactions of fast atomic and molecular ions with solid and gaseous targets (E. P. Kanter and Z. Vager),

(4) Atomic physics at ATLAS and the ECR source (R. W. Dunford and H. G. Berry)

In addition, a continuing program in theoretical atomic physics is staffed primarily by Visiting Scientists. Also, a small effort has started in atomic physics studies using synchrotron light sources in anticipation of an eventual major program in the future based on the 7-GeV Advanced Photon Source planned for construction at Argonne National Laboratory.

Experimental highlights of 1988 have included measurements at each of our accelerator facilities. At the Dynamitron, the new time-and-position-sensitive particle detector "SAM" was used for the first time to successfully measure the structure of the Al_3^+ cluster; at ATLAS, a two-photon coincidence experiment yielded precise lifetime measurements in hydrogen-like and helium-like nickel, as tests of quantum-electrodynamics; also at ATLAS, the new ECR source injector, part of the ATLAS upgrade, was used for several measurements on the dynamics of ion-atom collisions in a low-velocity range previously not accessible in any laboratory; at Blase, we developed a new high-resolution technique in fast-beam/laser spectroscopy, a Raman double-resonance technique, using it to measure hyperfine structures in ionized scandium. In addition, a systematic study using the rf double-resonance technique has been completed on the group IIA monoxides LaO, YO, and ScO.

Atomic physics experiments at ATLAS and the ECR source were coordinated by Dr. R. W. Dunford, and involved a wide range of visitors from Universities and National Laboratories outside Argonne. One set of experiments yielded precise lifetime measurements of metastable states in hydrogen-like and helium-like nickel. Previous measurements (at Argonne in nickel, and lower-Z ions elsewhere) had been standard beam-foil decay curve measurements which suffered from background and blending problems, and consequently were of too-low precision to test quantum-electrodynamic corrections to these lifetimes. Our coincidence measurements have a precision of better than 1%, and show good agreement with the latest theoretical values.

Another initiative in 1988 was the utilization for Atomic Physics experiments of low-energy highly-stripped ion beams from the electron-cyclotron-resonance source (ECR source), which is part of the current ATLAS upgrade. The ECR source is mounted on a 350-kV platform which allows a wide variation in beam energies of ions from the source. Using additional DOE equipment funds provided for this purpose in FY 1987, we constructed a beam-line and associated target/detection systems to take advantage of a "window of opportunity" that began about a year ago for atomic physics experiments at this unique facility. The physics projects possible with this type of arrangement form a strong overlap both with heavy-ion experiments using conventional accelerators such as ATLAS at Argonne, GANIL at Caen, GSI at Darmstadt, and also with the heavy-ion storage ring projects which are now in proposal form in the USA and under construction in Europe.

The high-voltage platform of the ECR source injector allows us to make measurements in a range of ion-beam velocities that is not possible at any other facility. This makes the installation unique for many experiments involving low-to-medium velocity multiply-charged ions. Initial experiments during 1988 have included both collision experiments and atomic structure measurements. We have completed a study of the velocity dependence of the cross sections for state-selective electron capture of helium-like oxygen on helium. Several experiments on observations of the secondary-electron production in ion-atom collisions studied the spectroscopy of auto-ionizing states in highly ionized neon. Both electron pickup and electron excitation are observed as a function of emission angle, and projectile velocity. The relative magnitude of these two processes varies strongly with projectile velocity. Initial measurements with a polarized sodium target, constructed and tested in 1988, were made using N^{5+} ions from the ECR source.

Close collaboration continues between Drs. William Childs, Linda Young and Gordon Berry on the laser aspects of our programs. Several new studies utilizing a new rf in-beam cavity have included precision hyperfine-structure measurements at Blase. In addition, the development of the polarized target for some of the ECR-based projects of Dr. Dunford has made strong use of our expertise in this area, particularly that gained by Dr. Young in her work on a polarized deuterium source.

Our theoretical program has been staffed by visitors during 1988. Professor R. Stephen Berry of the Chemistry Department at the University of Chicago has collaborated closely on new developments in the molecular structure program at the Dynamitron. Close collaborations with Prof. Jonathan Sapirstein from the University of Notre Dame have continued. Our measurements on the relativistic structures of three-electron systems, in several ongoing experiments in our ATLAS program, provide tests of his most recent calculations. The collaborative work is continuing on other relativistic atomic systems.

The appointment of Professor Peter Sigmund of Odense University in Denmark as an Argonne Fellow for one year will enhance several projects in the atomic program. In addition to several collaborations, he has begun work on a book on sputtering.

The Proceedings of the International "Symposium on Atomic Spectroscopy and Highly Ionized Atoms" (SASHIA), held August 15-21, 1937 at the Hickory Ridge Conference Centre at nearby Lisle, Illinois were edited by Drs. Berry, Dunford and Young, and published as a volume of Nuclear Instruments and Methods in May 1988.

V. HIGH-RESOLUTION LASER-rf SPECTROSCOPY OF ATOMIC AND MOLECULAR BEAMS

The atomic-beam laser-rf double-resonance technique provides a way for making extremely precise measurements of energy splittings in atomic, molecular and ionic systems. When used selectively to study families of related atoms or molecules it exposes the underlying trends clearly and has in recent years been very important in stimulating new *ab initio* calculations. This iterative process continues to lead to significant improvements in the theory.

We have devoted considerable effort to studying the spin-rotation and hyperfine interactions in alkaline-earth monohalides and more recently, the group IIIa monoxides. These have been chosen as a logical starting point for high-precision molecular studies because they are basically ionic systems with a single electron outside closed shells, and therefore relatively approachable theoretically. In addition to measuring the spin-rotation and hfs interactions themselves, the rotational and vibrational dependences have been determined. Performing the rf transitions in an electric field has led to measurement of the electric-dipole moments (through the Stark Effect), thereby stimulating considerable further theoretical efforts. The availability of such high-precision data has recently led to the use of super computers for the *ab initio* theory with promising results.

Systematic, high-precision measurements of the hfs of neutral, many-electron atoms have recently led to adaption of the multiconfiguration Dirac-Fock (MCDF) *ab initio* theory to make possible hfs calculations in heavy atoms. Comparison of the theoretical and experimental results, especially our recent ^{139}La I and ^{47,49}Ti I results, reveal unexpected deficiencies in the theory. Some of these are fundamental in nature and will hopefully lead to a real improvement in the theory.

A substantial effort this year went into measurements of the hyperfine structure of the radical PrO. This represents the first application of high-precision double-resonance methods to the study of a rare-earth diatomic, and was undertaken as a logical extension of the technique to a diatomic system containing a somewhat heavier metal than had been studied heretofore. The extremely high resolution of the method allowed a clean separation of the hfs of the upper and lower states, and indicated immediately that previous low-resolution results were in serious error. Unfortunately, however, a detailed interpretation of the results is limited by the present state of the theory. Hyperfine structure was also studied in two atomic systems, the light ^{47,49}Ti and the heavier ^{155,157}Gd. The other atomic experiment, the hfs of the $4f^7 5d^2 6s$ $^{11}F_{2-8}$ multiplet in ^{155,157}Gd was measured. The point of interest in this case was to determine whether the effective-operator theory of Sandars and Beck could be applicable to levels built on 3 open electron shells.

a. Hyperfine Structure of System XVII in PrO by Molecular-Beam Laser-rf Double Resonance (W. J. Childs and Y. Azuma)

The molecular-beam laser-rf double-resonance technique has been used to study the hfs of the lower ($\Omega'' = 3.5$) and upper ($\Omega' = 4.5$) electronic levels of system XVII of PrO. The method has allowed a clean separation of the hfs of the two levels for the first time, and shows that the conclusions based on earlier, low-resolution studies were wrong. Two regions of perturbation, centered near $J' = 22.5$ and 42.5, are shown to be associated with the upper state; the hfs of the lower state exhibits a smooth J dependence. Figure V-1 shows how the perturbations affect the observed wavelengths of the optical transitions. Figure V-2 shows in detail how the hyperfine components within particular lines are perturbed for J values in the vicinity of the weaker of the two perturbations. Substantial Λ-doubling is found, essentially all in the upper state and it is demonstrated that the lower-state hfs splittings are independent of which Λ-doubling branch the rf measurements are made in to within $\pm$ 1 kHz. The precision of the rf measurements of the lower-state splittings is about 10^3 times better than our present level of understanding, in sharp contrast to the situation for the $^2\Sigma^+$ states we have previously studied. A substantially more refined level of theoretical understanding will be required to take full advantage of the measurements, and it is hoped the work will stimulate progress toward this goal.

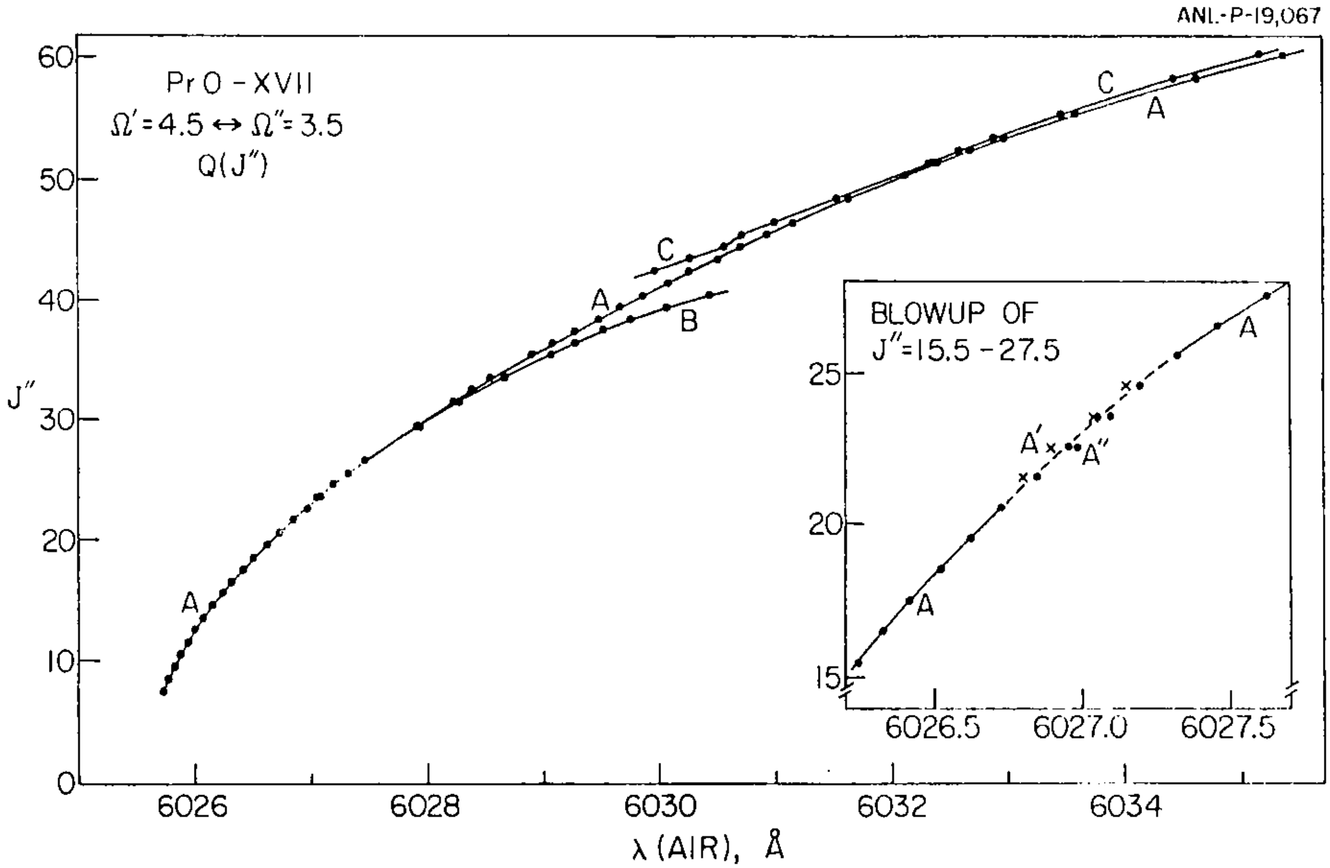

Fig. V-1. Plot of observed wavelength versus J-value for the Q(J") branch of system XVII in the optical spectrum of PrO. Upper-state perturbations appear near J = 22.5 and 42.5. The appearance of the Q(J") lines for 20.5 ≲ J" ≲ 24.5, i.e in the vicinity of the weaker perturbation, is shown in Fig. V-2.

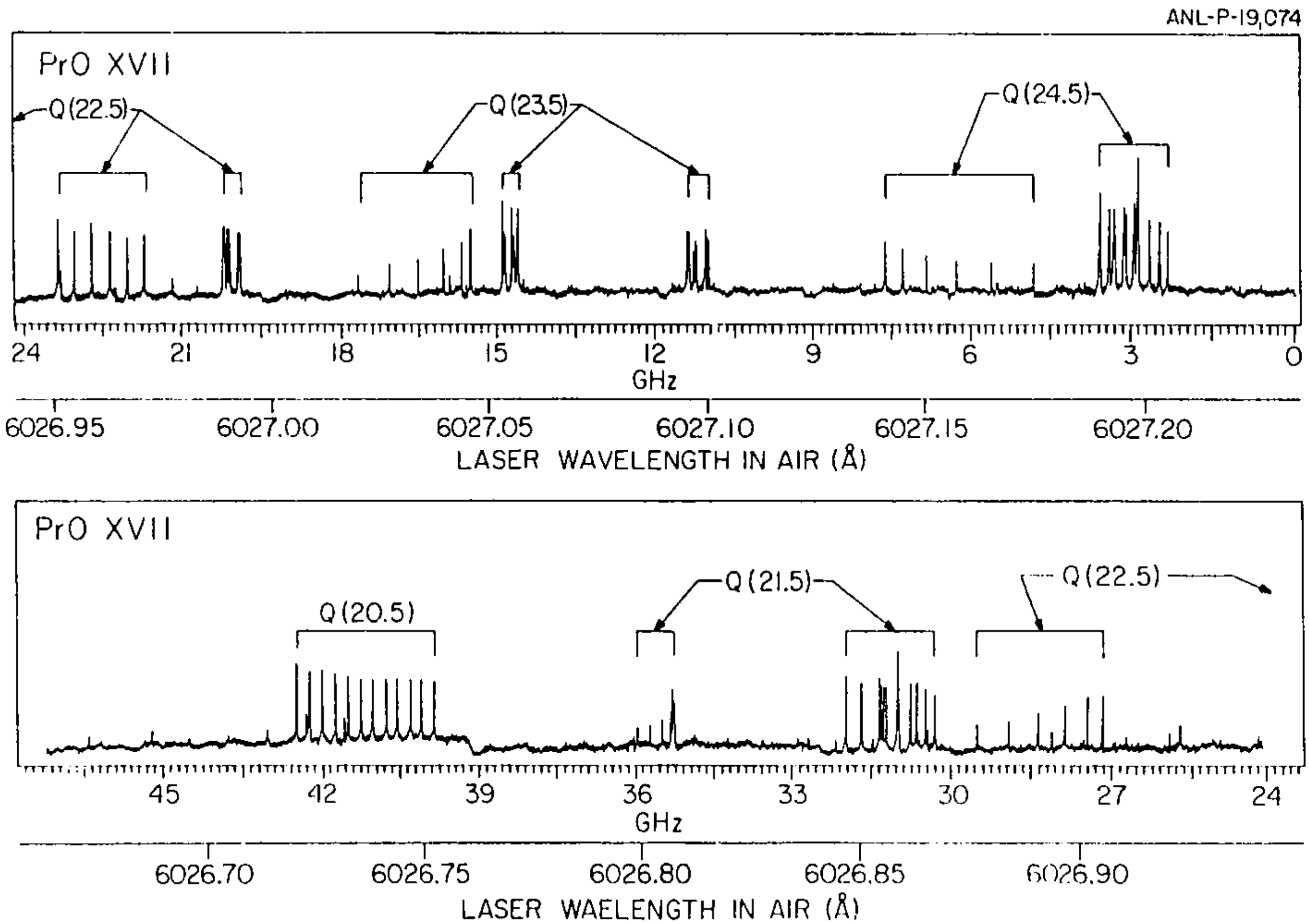

Fig. V-2. Appearance of the Q(J") lines of system XVII in PrO for 20.5 ≲ J" ≲ 24.5. The strongly J-dependent nature of the (hyperfine) splitting of these lines gives evidence of a strong perturbation, in this case of the upper state.

b. Hyperfine Structure of the $4f^75d^26s$ ^{11}F Term of ^{155,157}Gd I by Atomic-Beam Laser-rf Double Resonance (W. J. Childs)

The $4f^75d^26s$ ^{11}F multiplet in ^{155,157}Gd was chosen for study in part to determine whether the Sandars-Beck effective-operator theory of atomic hfs could be usefully applied to levels built on 3 open electron shells. The conclusion, based on precise measurements of the magnetic-dipole (A) and electric-quadrupole (B) hfs constants for 8 levels of the multiplet, is that the theory is surprisingly good if the levels in question are sufficiently pure. The Gd levels have been reported to be about 98% pure L-S coupled and appeared to be almost ideally suited for a test case. Because of this success, and because studies are now being made of the hfs of ever increasingly complex atomic systems, general expressions have been derived, based on the Sandars-Beck model and the rules of Racah algebra, for hfs arising from any number n ($n \lesssim 3$) of open electron shells. The study also identifies an interesting perturbation between the J = 5 levels of the two terms $4f^75d^26s$ ^{11}F and $4f^75d6s^2$ ^7D. It is independently detectable from (1) the magnetic-dipole hfs, (2) the electric-quadrupole hfs, and (3) the fine-structure intervals. Unfortunately the theory is not yet well enough developed for such complex electron configurations to investigate the perturbation theoretically. Hfs constants are also given for a number of very-highly-excited states, as are isotope-shift values for many optical lines.

c. Hfs of $3d^2$ ^3P and ^1D Levels of $^{47,49}Ti$ I (W. J. Childs and Y. Azuma)

Over the years a number of measurements of the hfs of atomic states based on orbiting ($\ell > 0$) electrons have shown the presence of contact ($\ell = 0$) hfs. In some cases this has even been the dominant contributor to the hfs, as in the $5d^3$ ^4F levels we investigated last year in ^{139}La I. Measurements in the $3d^24s^2$ configuration of $^{47,49}Ti$ I show a similar effect for the $^3P_{1,2}$ levels, but not for other levels of the same configuration. A similar result was found recently in BLASE measurements on the $3d^2$ $^3P_{1,2}$ levels of Sc II. New ab initio MCDF calculations by Cheng for Ti I and Sc II do not predict the large contact contributions, and it is now clear that higher-order calculations and/or a qualitatively different theoretical approach must be used to underestand the phenomenon. The collective contributions of all of these experiments have been necessary to isolate and spot-light the problem clearly. We believe the source of the contact hfs is polarization of closed inner s-shells by the outer d-electrons through the Coulomb interaction. Even a very slight distortion can result in a very large magnetic field at the nucleus and consequently a large (contact) magnetic-dipole hyperfine interaction.

d. Efforts to Produce Useful Beams of Selected Diatomic Radicals for High-Resolution Spectroscopic Study (W. J. Childs, T. C. Steimle, and Y. Azuma)

Production of thermal beams of diatomic radicals almost always requires doing chemistry in the beam source, since few of them can be produced simply by heating a single component in an oven in vacuum. We have attempted to produce beams of the following diatomics: CuO, Al_2, CaH, EuO, YbO, TiO, TiN, CeF, SnF, CuS, SmO, YS, CoO, SrI, SrF, and YF. Of these we have succeeded in making usable beams of TiO, CeF, YS, SrI, SrF, and YF.

VI. FAST ION-BEAM/LASER STUDIES OF ATOMIC AND MOLECULAR STRUCTURE

The thrust of our program is the high-precision spectroscopic study of ionic species. Experimental studies of this type provide the most stringent tests of ab initio calculations of atomic and molecular structure. Such studies, however, have been notoriously difficult due to problems in the generation of the ions in an environment suitable for precision studies. Usually production of ions is via a plasma discharge, an extremely unfriendly environment for high-precision spectroscopy due to interactions between the ions and neutrals (typically 10,000 times more abundant than ions). However, it has been recognized that extraction of the ions from the discharge and formation into an ion beam provides one with a suitable, perturbation-free environment.

Towards this end in the past year we have used the recently-completed BLASE facility to make measurements of hyperfine structure (hfs) in some singly-ionized systems (scandium, N_2^+, thulium). The experiments have been supported by ab initio multiconfiguration Dirac Fock (MCDF) calculations. The MCDF calculations show substantial (in some cases > 400%) disagreement with experiment.

As part of a continuing upgrade of the BLASE facility, we have incorporated an rf-resonance region in the beam-line. This has improved the precision to which we can measure lower-state intervals by a factor of ~ 100. The laser-rf double-resonance technique was used in measurements of hfs in Sc^+.

Attempts to use this rf-resonance region at low frequencies revealed modulations of the beam velocity profile which render the laser-rf double-resonance technique useless. We have developed an alternative scheme which imposes the rf on the laser rather than on the ion beam. In this technique, a stimulated-resonance Raman transition can be induced using the output of a single phase-modulated laser. The resonance can be measured with rf precision and its width is transit-time limited.

A long, magnetically-shielded, optical-interaction region has been designed and is currently undergoing construction. The new interaction region will further refine the stimulated-resonance Raman technique and enhance overall sensitivity in laser-induced fluorescence experiments.

Another area of active research concerns the development of an ion source with high metastable content. The development of such a source is essential for the study of QED and relativistic effects in two-electron systems. Current efforts center around a microwave discharge source.

BLASE TECHNICAL ACHIEVEMENTS

a. Thulium Laser-Induced Fluorescence Measurements
(T. Dinneen,* N. B. Mansour and L. Young)

We have measured hyperfine structure (hfs) splittings in some low-lying levels in Tm II. These levels arise from the relatively simple configurations $4f^{13}$ 5d and $4f^{13}$ 6s. The electronic levels of ^{169}Tm II exhibit a particularly simple hyperfine structure. Since the nuclear spin equals 1/2, the levels are split into only two hyperfine components whose separation is determined exclusively by the magnetic dipole interaction. The magnetic coupling constant A, determined by fast-ion-beam laser spectroscopy (FIBLAS), has an accuracy ranging between 1 and 2 MHz. These values are compared with the multiconfiguration Dirac-Fock (MCDF) *ab initio* calculations for the lower states. Hfs of configurations explicitly containing open s shells are found to be in substantial disagreement with MCDF calculations.

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b. N_2^+ Laser-Induced Fluorescence (N. B. Mansour, T. Dinneen* and L. Young)

The fine and hyperfine structure has been observed in 21 rotational lines of the (0,1) band of the B $^2\Sigma_u^+$ - X $^2\Sigma_g^+$ system. The fine and hyperfine structures of 9 rotational lines of the (1,2) band have been resolved for the first time using FIBLAS.

The hfs measurements show significant perturbation of the B states by high-lying vibrational levels of the A Π_u state (v_A=9,10,11). Analyses of these measurements are in progress in order to better understand the perturbation, deperturb the system, and deduce accurate spin-rotation constants and hyperfine-coupling constants of the B and X states. From the Laser-induced fluorescence measurements we have determined a rotational temperature of 1400 K and a vibrational temperature of 23000 K.

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c. <u>The Rf System at BLASE</u> (C. Kurtz, L. Young, N. B. Mansour and T. Dinneen*)

In order to carry out a laser-rf double-resonance (LRDR) measurement it is necessary to achieve a population difference between adjacent hyperfine levels. In an LRDR measurement we tune the laser wavelength to a particular hfs transition F->F' and deplete selectively the F state. This is accomplished by introducing a pump region in front of an rf excitation cavity operated at the same post-acceleration voltage as the probe region. The ions then enter the rf region, where the laser is off resonance, and the rf field is scanned over a predicted frequency interval. The population of the pumped level is altered, at resonance, by magnetic dipole hyperfine transitions of the type $F \leftrightarrow F\pm1$ and an rf resonance is detected in the probe region.

The rf region consists of a 50-ohm transmission line of the tri-plate design. The center strip is 50-cm long, and is placed symmetrically between two ground plates constructed of heat-treated permalloy to provide magnetic shielding. The travelling wave field is applied at one end, between the center strip and one ground plate, and is terminated by a 50-ohm load.

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d. <u>Scandium Laser-Induced Fluorescence and RF Measurements</u> (N. B. Mansour, T. Dinneen* and L. Young)

The hyperfine structure of all levels of the metastable $3d^2$ in Sc II has been measured with high precision by collinear fast ion laser-rf double-resonance spectroscopy. This technique made possible the resolution of optically unresolved hfs components (see Fig. VI-1). We derived the magnetic dipole and the electric quadrupole hyperfine interaction constants of $^3F_{2,3,4}$ levels not previously investigated and also improved the precision of our results by at least a factor of 150. Our measurements enabled us also to determine the hfs constants of the upper levels in the 3d4p configuration with better precision. The combined results are compared with multiconfiguration Dirac-Fock (MCDF) *ab initio* calculations. A manuscript reporting these results has been submitted for publication.

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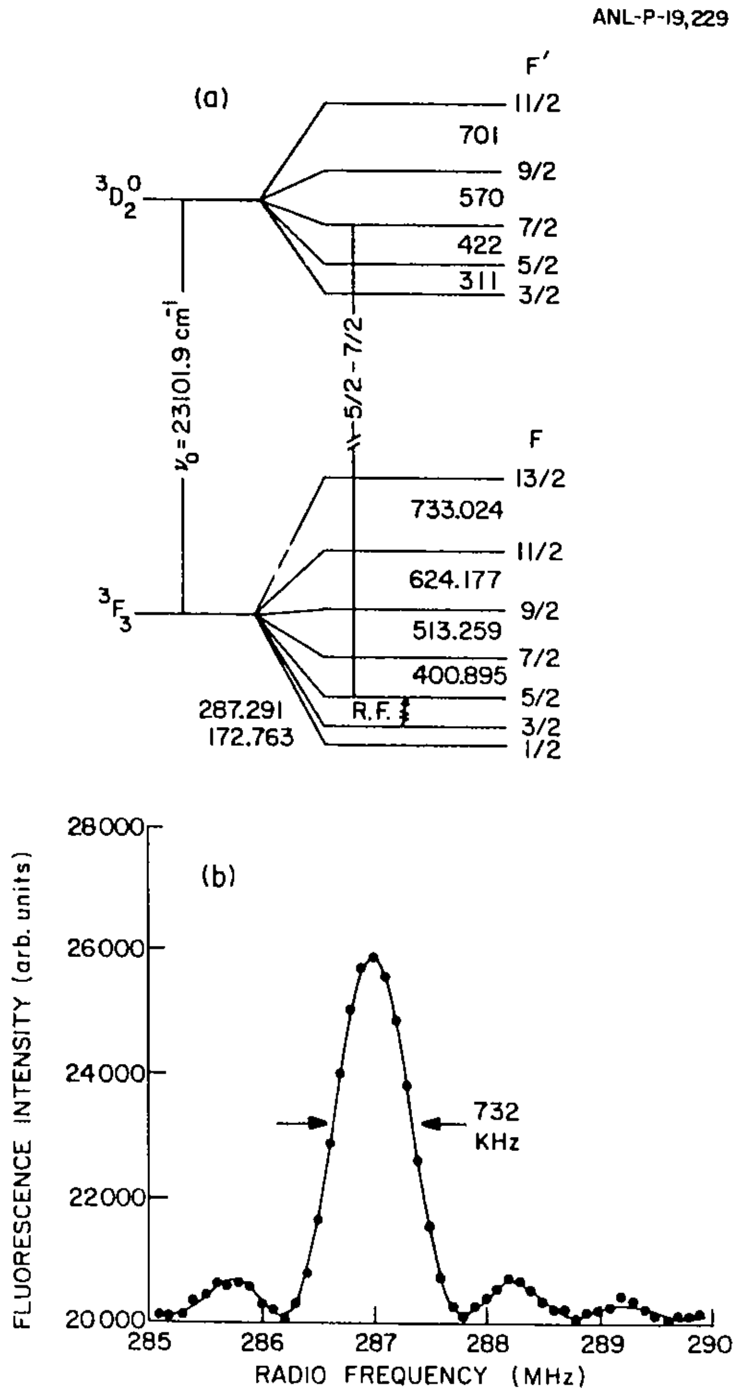

Fig. VI-1. The energy level diagram of the hyperfine level of the $^3F_3$ and $^3D_4{}^0$ states is shown in (a). A laser-rf double-resonance spectrum for the transition F_1=3/2→F_2=5/2 in the $^3F_3$ state is shown in (b). The solid line is a fit to a Rabi two-level model. The linewidth obtained from the fit is 732 kHz which is consistent with the ion transit time in the rf region of 1.08 μs at 50-keV energy.

e. Raman Double-Resonance Technique (L. Young, T. Dinneen* and N. B. Mansour)

While using the laser-rf double-resonance system described above for observations on fast ions, we observed a difficulty at low radio frequencies. Instead of observing a single resonance, we observe a periodic signal with a frequency corresponding to the transit time of ions within the radio-frequency field. We identified the origin of these modulations from the varying phase of the rf at the two end regions which develop a differential velocity distribution in the ions.

We have developed an alternative scheme at low resonance frequencies which avoids these problems. Instead of imposing the radio frequency on the ions, we apply it as a sideband on the laser frequency. This then becomes equivalent to stimulated resonance Raman spectroscopy, where one laser frequency corresponds to the exciting transition, and the sideband frequency is the de-exciting transition, in our case, to a neighboring hyperfine level. The technique retains the high resolution of radio frequency, and the resonance widths are determined by the transit time in the resonance region (see Fig. VI-2).

We have applied this technique for the first time in measuring hyperfine intervals in Sc II.

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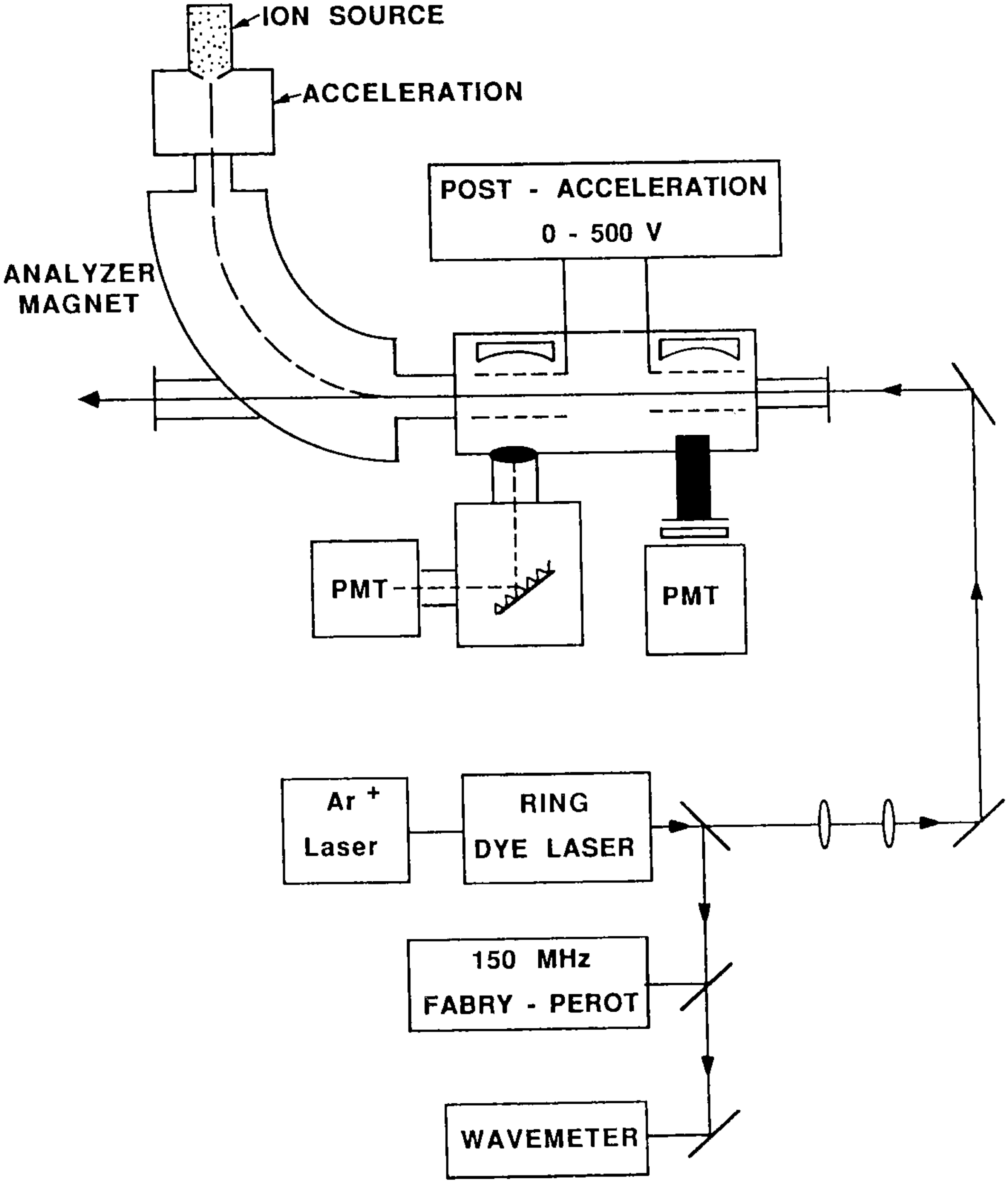

Fig. VI-2. Schematic diagram of the upgraded experimental apparatus used in the laser-rf double resonance experiments. The pump region where optical pumping occurs, the rf region where repopulation takes place, and the probe region where fluroescence is detected are shown.

f. Extracavity Laser Bandshape Modification
(L. Young, C. Kurtz, N. B. Mansour and T. Dinneen*)

In order to better match the Doppler profile of the ion beam, it is possible to control the spectral density of the laser through electro-optic phase modulation. We have constructed and tested a wide-bandwidth electro-optic modulator. This has allowed arbitrary control of the laser bandwidth from 1-MHz to 800-MHz FWHM. The large value exceeds previously reported bandwidths using acousto-optic modulators by an order of magnitude. This system will enable us to address all velocity classes present in the ion beams with modest laser powers.

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g. Lithium Ion Production
(C. Kurtz, T. Dinneen,* N. B. Mansour, L. Young and H. G. Berry)

The production of highly-excited metastable ions is a requirement for many of the laser-induced fluorescence measurements. The Li^+ ion has a 1s2s ^3S state at 60 electron volts above the ground-state, much higher than any ion previously attempted with our Danfysik 910 ion-source. However, this is the first 2-electron ion of the sequence which we intend to study in tests of relativistic atomic theory.

We found that the population of this state is enhanced under the source conditions which optimize the production of doubly-charged lithium ions. A laser-induced fluorescence study of the 1s2s ^3S - 1s2p ^3P transition of Li II was successful. However, this source will not be suitable to excite more highly-ionized ions in this sequence.

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h. Microwave Source

(C. Kurtz, T. Dinneen,* N. B. Mansour, L. Young and H. G. Berry)

We are developing an ion source, to be attached to the BLASE accelerator, which will provide multicharged ions, populated in highly-excited metastable states. We have begun work on a microwave-excited source, similar to one used at the University of Missouri, which produced He^{++} and Ne^{5+} ions. Our first tests of this source with a low-power diathermy unit (up to 50 watts microwave power) have been made with helium and neon. Further experiments are in progress with a higher power microwave source. To maintain a narrow velocity distribution of ions from the source, we need to carefully stabilize the microwave power. Work is in progress on improving the stability.

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

Tightly-collimated beams of molecular ions with energies variable in the range 0.5-8.0 MeV are directed onto thin (~30 Å) foil or gaseous targets. The distributions in laboratory velocities are measured with high resolution (~0.005° and ~200 psec) 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 unique to the use of molecular-ion projectiles. In particular, we have been able to deduce the structures of the incident molecular ions. These two different aspects of the work are mutually interdependent. In order to derive structure information about a given molecular ion, one needs to know details about the way the dissociation fragments collectively interact with the target in which the dissociation occurs. Similarly, a knowledge of the structure of the incident molecular clusters is important in understanding the physics of their interactions with the target. Our work therefore began with careful studies involving beams of the simplest and relatively well-understood diatomic molecular-ions (H_2^+, HeH^+, etc.). Even with these, several new and interesting phenomena have been encountered (e.g., the interactions between the molecular constituents and the polarization oscillations that they induce in a solid target, the marked differences in dissociations induced in gases as compared with those in foils, the anomalously high transmission of some molecular ions through foils, and striking electron capture phenomena when compared to atomic ions). Now that those studies have elucidated the important physical processes affecting the penetration of molecular ions through matter, we have concentrated our efforts on using this knowledge to study the structures of the molecular ion projectiles. The development of multiparticle detectors have enabled us to directly measure the densities of atomic nuclei within small polyatomic molecules. These experiments provide radically new sources of information on the structures and vibrations of molecular ions which have already made significant contributions in guiding theorists.

The bulk of our effort during FY 1988 was directed toward the study of several polyatomic molecular ions and cluster ions as well as a major expansion of the apparatus to permit studies of a much broader set of molecules than has hitherto been accessible. Additionally, these studies have also afforded us the opportunity to develop new analysis methods for studying molecules with many degrees of freedom.

a. The Vibrational Dynamics of the Methane Cation
(E. P. Kanter, Z. Vager, and D. Zajfman*)

The methane cation has been the subject of numerous theoretical and experimental papers in recent years. While the neutral methane molecule exhibits a highly symmetrical tetrahedral geometry, it has long been known that the Jahn-Teller effect would cause its ion (CH_4^+) to be distorted from tetrahedral symmetry. Despite this well-known prediction, the detailed structure of this ion remains an open question. Our Coulomb-explosion experiments had previously demonstrated a time-averaged structure that was consistent with the findings of electron spin resonance spectroscopy. However, by exploiting newly-developed analysis techniques, we have now been able to obtain a far more detailed picture of nuclear motions within this molecule including all of the correlations.

The Coulomb interaction Hamiltonian is invariant under both rotations in configuration space (R-space) and permutations of the identical protons. Therefore, the use of symmetry coordinates in V-space (the space defined by the final velocity vectors of the fragments) can result in a simplified description of the density of measured events that can later be related to the R-space symmetries. In our analysis of CH_4^+, we used appropriate coordinates to represent the distortions of the molecule from a symmetric tetrahedral geometry. Four of these coordinates, which describe stretching of the CH bonds, revealed comparatively rigid motions (i.e. $\Delta r/r$ is quite small). The angular degrees of freedom however appear to be quite floppy. To explore this floppy motion, we concentrated our analysis on three of those coordinates relating the angular changes.

When viewed in these coordinates, we find a highly fluxional molecule with significant densities at C_{2v} and C_s geometries, but with a density minimum at the tetrahedral (T_d) origin. By comparison, the same analysis of data resulting from an NH_4^+ Coulomb-explosion measurement shows quite different results. The NH_4^+ ion is isoelectronic with the neutral CH_4 molecule. It is expected to manifest a T_d symmetry. Indeed our results show only one structure with a single peak at the origin corresponding to a tetrahedral symmetry.

*The Technion, Haifa, Israel

While the CH_4^+ data may represent the behavior of the molecule in its ground state, we cannot at present rule out the possibility that the ensemble produced by low-energy electron impact on methane is excited. A small excitation energy, concentrated in these angular coordinates, would induce fluxional behavior. With higher potential barriers near the C_s structures, the lower classical velocities would lead to regions of high densities. With such an ensemble, the true potential minima (possibly, e.g. the C_{2v} geometries) would appear less dense because of the increased velocities in these regions imparted by the excitation energy.

It is important to realize that such data describe not only the 3-dimensional probability densities for finding a single nucleus within the molecule, but also all possible correlations between the constituent nuclei. Such a direct measurement of the square of the multidimensional wave function of a many-body system is a challenge by itself which, as far as we know, has never been achieved in any field of physics. This example demonstrates the densities in the nuclear coordinates for a truly dynamical situation. It stresses the quality of information that can be obtained from Coulomb-explosion experiments with precise control of the production mechanism of the measured species. This is the trend that will be pursued in future experiments.

b. <u>Stereostructure of Aluminum Cluster Ions</u>
(A. Belkacem, E. P. Kanter, R. Mitchell*, Z. Vager, and B. J. Zabransky)

The study of small clusters of atoms has been a very rapidly developing field during the past few years. Because of the wide range of physical and chemical properties that these objects exhibit, they represent an entirely new class of chemically active species which are already finding important applications. Despite this intense interest, there is virtually no direct information on the geometrical forms of small clusters. Thus, the idea of applying Coulomb-explosion imaging to these molecules has generated considerable interest in the scientific community.

Beyond the study of the small hydrides, it had previously been presumed that these techniques would be inapplicable to the study of clusters of identical atoms. Recently however, in our study of C_3^+, we have demonstrated that these methods can indeed provide important structural information on small clusters. In particular, we were able to clearly deduce symmetry features in the cluster geometries.

With the completion of our new SAM heavy-ion detector system this year, we were able to attack the problem of Al_3^+. Because this molecule is so heavy (it represents the slowest molecule studied to date) the problems introduced by small-angle multiple scattering in the stripping medium were more severe than in previous experiments. Nevertheless, we have been able to deduce an "average" geometry by comparing the data (in properly symmetrized coordinates) to our earlier C_3^+ results and to synthesized distributions generated by Monte-Carlo simulations. The preliminary findings indicate a very floppy linear structure (in contrast to the comparatively rigid ring observed for C_3^+). Although there have been theoretical investigations of the neutral Al_n clusters, owing to the lack of experimental information, no calculations of the ion structures have yet been carried out. We have now stimulated work in this area by several theorists and we hope, when those results become available, to improve our analyses.

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c. Development of a Segmented-Anode MWPC (SAM)

(A. Belkacem, E. P. Kanter, R. Mitchell*, Z. Vager, and B. J. Zabransky)

Our experiments with molecules containing protons and 2 or more heavy ions have been severely hampered because of the finite area of the MUPPATS detector. As a result, we have either sacrificed charge-state information (as was the case for $C_2H_3^+$) or information about the proton geometries. This has limited our most extensive studies before now to molecules of the form XH_n^+. For protonated acetylene, although we could make qualitative statements about the structure, we could obtain neither bond length nor vibrational information. For the series $C_3H_n^+$, we were limited to studying the carbon geometries only.

In an effort to alleviate these limitations, we have developed a radically new detector specifically optimized for heavy-ion detection. The new detector is a single-stage multiwire proportional counter with a unique anode structure consisting of a plated-through PC board which interweaves 3 non-intersecting "wire planes" onto a single anode board. As a result, the 3 signals observed for each particle are fast anode signals (rather than the slower cathode signals used in the older MUPPATS detector). Because of this triply-redundant time measurement (and instrumentation for individual "wire" readout), we have been able to obtain time resolution below 200 psec with this new detector. The improved time resolution is important for the heavy-ion fragments because of their slower motions relative to the center of mass of the molecule. Experiments carried out so far with this new detector system have included studies of Al_3^+ and $^{14}N^{15}N^{++}$.

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Concurrent with the detector-development program, improvements in the computer interfacing of the readout electronics and conversion to the DAPHNE data-acquisition system has increased our rate of data collection by more than an order of magnitude. This is a significant factor in our ability to study molecules with many degrees of freedom where our analysis methods had previously been limited by statistics.

With this new detector, we will also be able to separate the heavily-ionizing heavy ions from the more weakly-ionizing protons (on the MUPPATS detector) and thus be able to improve the detection efficiencies for molecules containing both types of fragments. Additionally, the large area of the new detector (25×50 cm^2 rectangle) has permitted sufficient electrostatic deflections to resolve heteronuclear heavy-ion fragments (as in the case of our $^{14}N^{15}N^{++}$ data).

d. Ion Source Development
(A. Belkacem, E. P. Kanter, Z. Vager, and B. J. Zabransky)

A new research aim of this work has been the study of atomic clusters. While previous experiments with carbon clusters were able to exploit existing ion sources, this proved unfeasible for aluminum cluster ions. During the past year we solved this problem by modifying a conventional radiofrequency ion source to serve as a simple sputter source. In this arrangement, 80-keV Kr^+ ions were used to sputter ions from an aluminum surface, producing secondary Al_3^+ ions which were then studied in Coulomb-explosion experiments. This arrangement proved extremely powerful and during the next year we will attempt to use these same techniques to produce ionic clusters of boron, beryllium, carbon, and lithium.

VIII. THEORETICAL ATOMIC PHYSICS

Our theoretical program in 1988 was limited to a few visiting theorists. During the year we made substantial efforts to locate a permanent staff member for the theoretical program, but were not able to fill the position. Prof. Jonathan Sapirstein of Notre Dame, was not able to come to Argonne, but has continued to collaborate with us on the relativistic structures of three-electron systems. Our measurements on these ions continue at ATLAS in collaboration with the group of Prof. Eugene Livingston. The collaborative work is continuing with Prof. Sapirstein on other relativistic atomic systems.

Professor R. Stephen Berry of the University of Chicago has a part-time appointment with the Physics Division and collaborated strongly in our development of the theoretical interpretation of measurements in the Coulomb explosion program. We expect increased collaboration with him in the future.

Prof. Peter Sigmund (Odense University) has joined us as an Argonne Fellow for one year beginning in September 1988. He has begun work on various aspects of the Coulomb explosion program, and is working on a comprehensive treatise on stopping theory. The work of Dr. Christopher Bottcher, who was a visitor in 1987, was completed with a publication on highly-charged ion collisions.

a. Production of Heavy Leptons in Ultra-relativistic Heavy-Ion Collisions
(C. Bottcher and M. R. Strayer*)

Substantial progress on this project was achieved during and following the year Dr. Bottcher spent at ANL. The expected cross sections for producing muon and tauon pairs at RHIC are large enough to be intersting for observations. We have finally succeeded in expressing the amplitudes as Fourier components of the invariants of the time- dependent electro-magnetic field,

$$E \bullet E - B \bullet B \text{ (scalar)}, \ E \bullet B \text{ (pseudoscalar)},$$

so that our model is automatically Lorentz and gauge invariant.

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b. Charged-Particle Wake and Stopping Theory
(Ali Belkacem, H. Esbensen, and P. Sigmund)

A general theoretical scheme has been developed to characterize the polarization field set up by a heavy charged particle travelling through a dense medium, with a view to analyzing wake phenomena and determining stopping powers. The scheme goes beyond the first Born approximation and is thus applicable to the medium-velocity range where many experiments on wake phenomena have been performed. Existing theories based on more restrictive assumptions (classical harmonic oscillator, free electron gas, first Born approximation, etc.) all emerge from the general formalism as special cases. Problems focused upon up till now are the relative importance of an energy gap and the plasma frequency on the stopping power and wake field in an insulating medium, and the "Barkas" correction to the classical wake field. An attempt is being made to resolve a standing discrepancy in the literature on the Barkas effect in the stopping power of a free electron gas.

c. Coulomb Explosion and Multiple Scattering (P. Sigmund)

A theoretical scheme is being developed to deconvolute the effect of multiple scattering on the trajectories of Coulomb-exploding molecular ions from measured detector signals. The starting point is the Boltzmann equation including scattering and force terms, which has been linearized in the multiple scattering angle. The relative merits of various schemes of deconvolution are being investigated.

d. Charged-Particle Stopping Theory (P. Sigmund)

Work is continuing on a monograph on the theory of stopping and ranges of charged particles, and on a comprehensive tabulation of stopping power and straggling of heavier ions [(work requested by the International Commission of Radiation Units and Measurements (ICRU)].

e. Cluster Bombardment (P. Sigmund)

Cluster bombardment of solid targets in the keV/atom energy range leads to a number of unusual features of the kinematics of recoil events which cannot be found in experiments involving atomic bombarding ions. Mostly qualitative aspects have been explored up until now, in relation to some surprising experimental results reported recently. A paper is in press.

IX. ATOMIC PHYSICS AT ATLAS AND THE ECR SOURCE

The program in atomic physics at the Argonne Tandem Linear Accelerator System (ATLAS) involves in-house experimenters and collaborations with outside groups. Experiments have included: X-ray and VUV spectroscopy, studies of atomic collisions, heavy-ion desorption of biomolecules, Auger electron spectrosopy and studies of Rydberg atoms. Prior to 1986 atomic physics experiments were performed using general- purpose beamlines and facilities which were designed for research in nuclear physics, but in 1986 a dedicated atomic physics beamline was set up greatly facilitating the use of ATLAS for atomic physics.

The first stage of the Uranium Upgrade of ATLAS will be completed in early 1989. The goal of this project is to replace the present tandem injector of the linac with an ECR ion source and a new injector linac. The new injector will ultimately extend the mass range of ions that can be accelerated up to uranium (heaviest mass currently available is ^{127}I) and increase the beam intensity by one to two orders of magnitude. The increase in beam intensity will be particularly useful for precision spectroscopy because low- statistics experiments which have not been possible up to now will become practicable. In addition, the new injector will allow experiments with more highly-charged ions because useful beam intensities can be obtained from the higher charge states obtained after stripping.

The atomic physics program has already benefitted from use of the ECR ion source which was built as part of the ATLAS upgrade. This source provides intense beams of slow, moderately charged ions, therefore it is an excellent tool for atomic physics. It will be available for atomic physics during periods when it is not being used to inject ATLAS. The ion source was first run sucessfully in October 1987 and the first atomic physics experiment was begun about a week later. The beam line was initially set up in a temporary location in the old West Target Room at ATLAS. In the 1988, the facility was moved to its permanent location in a recently completed building addition. We also installed a second short beamline to the facility and a switching magnet which is used to direct the beam from the ATLAS injection line to either of the two atomic physics beamlines. A unique feature of the ATLAS ECR facility is that the ion source is on a 350-kV high voltage platform. This provides for increased flexibility in the experimental program compared to other ECR ion source facilities where accelerating potentials are at most 20 kV.

a. Spectroscopy of Helium-Like and Lithium-Like Ions
(H. G. Berry, A. E. Livingston*, A. S. Zacarias*, Y. N. Lu*, and R. W. Dunford)

A program is in progress to make precision measurements of transition energies in helium-like and lithium-like ions of high nuclear charge (Z). Such measurements provide important tests of quantum electrodynamics and atomic structure calculations. We recently completed analysis of a measurement of the 1s2s $^3S_1$ - 1s2p $^3P_2$ transition energy in helium-like nickel ($^{58}Ni^{26+}$) which yields a value of 226.21 ± 0.06 Å for the transition wavelength.

In the past year we extended our measurements to higher Z, using a bromine beam from ATLAS. In the experiment, we observed spectra of two- and three- electron bromine (Z= 35) using the 2.2 meter grazing incidence spectrometer at the atomic physics beamline. The main goal of the bromine run was to obtain precision measurements of lithium-like bromine. The interest in lithium-like ions comes from recent theoretical progress by Johnson and Sapirstein at Notre Dame. Their work utilizes many-body perturbation theory. The calculations include, for example, explicit non-perturbative computation of higher-order Breit interaction contributions and should provide the first unambiguous screening corrections to the Lamb-shift contributions in three-electron ions.

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b. Lifetimes of the 2^1S_0 State of Helium-like Ni^{26+} and the $2^2S_{1/2}$ State of Hydrogen-like Ni^{27+}
(R. W. Dunford, M. Hass, E. Bakke, H. G. Berry, C. J. Liu, M. L. A. Raphaelian,* L. J. Curtis†)

In the past year we completed precision measurements of the lifetimes of both the $2^2S_{1/2}$ state of hydrogen-like Ni^{27+} and the 2^1S_0 state of helium-like Ni^{26+}. These states decay to their ground states primarily by the emission of two photons. In the case of the $2^2S_{1/2}$ state there is also an M1 decay branch (branching ratio 17% at Z=28). Our experiment utilizes the standard beam-foil time-of-flight technique except that we require a coincidence between the two photons emitted in the decays.

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The singles spectra from the two-photon decays form a continuous distribution with a broad maximum at half the transition energy which drops to zero at either endpoint. The sum of the energies of the two photons is equal to the transition energy (about 8 keV). Former measurements of the lifetimes of these states in other hydrogen-like and helium-like ions were based on singles rates. In this case, it is difficult to obtain a high- precision result because of uncertainty in the shape of the background under the two-photon continuum and uncertainty in the dependence of this shape on foil-detector separation.

Our measurements were obtained in two separate runs at ATLAS using nickel beams at energies of 376 MeV and 674 MeV. After acceleration, the ions were stripped in a thick carbon foil and either the 26+ or the 28+ charge state was magnetically selected and directed to the atomic physics beamline. In the experimental area, a thin carbon target (12 g/cm^2) was moved relative to three fixed Si(Li) detectors using a precision translation device. The coincidence rate was measured as a function of foil-detector separation to determine the lifetime. There was also a small ion-implanted, passivated X-ray detector attached to the target holder which was used for normalization.

Our result for the lifetime of the helium-like state is 156.1(1.6) ps which is slightly higher than the theoretical value of 154.3(0.5) ps calculated by G. W. F. Drake of Windsor, Ontario. This result provides a test of the relativistic corrections which increase the calculated lifetime by 4.3 ps. For the decay of the $2^2S_{1/2}$ state in hydrogen-like Ni^{27+} we find a lifetime of 217.1(1.3) ps which agrees with the theoretical value of 215.65 ps calculated by F. A. Parpia and W. R. Johnson of the University of Notre Dame. This result is the first measurement of the $2^2S_{1/2}$ lifetime to be sensitive to the relativistic correction to the two-photon decay rate and it is also the most sensitive test of the M1 contribution to this decay rate.

c. Measurement of the 1S Lamb Shift in One- and Two-Electron Calcium
(R. W. Dunford, H. G. Berry, R. C. Pardo, M. L. A. Raphaelian,* R. D. Deslattes†, P. Indelicato†, and E. Kessler, Jr.†)

An important program in progress at ATLAS concerns the measurement of the 1S lamb shift in one- and two- electron calcium ions in collaboration with R. D. Deslattes of NIST. These measurements will test Quantum Electrodynamics (QED) and Relativistic Quantum Mechanics. We plan to use the accel-decel technique in which ions are accelerated, stripped to bare nuclei, then slowed down and delivered to a gas target where they pick up electrons under single-collision conditions. The deceleration is required both to reduce Doppler shifts and also to obtain adequate cross sections for electron pickup in the gas target. The importance of using a gas target is that single-electron pickup is highly favored and so clean, symmetrical spectral lines, uncontaminated by spectator electrons are obtained. To date, we have completed some preliminary tests at ATLAS to develop the decelerated beams of Ca^{20+} and Ca^{19+} ions and the gas target necessary for the measurement. We also determined the X-ray yields which could be produced in the gas target. In the past year, the high-precision X-ray spectrometer which will be needed for the experiment has been developed at NIST. Tests of the efficiency of the spectrometer are in progress. In the next year we intend to install the spectrometer on the atomic physics beamline at ATLAS.

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d. State-Selective Electron Capture

(R. W. Dunford, C. L. Liu, H. G. Berry, P. J. Billquist, R. C. Pardo, B. J. Zabransky, K. O. Groeneveld,* M. Hass, and M. L. A. Raphaelian†)

One program at the ECR ion source is the study of state-selective electron capture using the technique of Photon Emission Spectroscopy. Our goal is to extend existing measurements of subshell selective electron capture which have been done at low energy to intermediate energy taking advantage of the 350-kV platform. In addition to their importance in extending tests of theoretical calculations to intermediate energy, measurements in the 10-150-keV/amu velocity regime are useful to fusion research because collisions between plasma ions and neutral beams in tokamaks involve velocities of 40-150 keV/amu. Photon emission following these collisions is used to measure impurity concentrations, study ion transport, and determine ion-velocity distributions.

We have completed data analysis for a measurement of the cross sections for electron capture by O^{6+} incident on a He gas target. Photon emission cross sections have been measured for collision velocities from 2 to 105 keV/amu for transition wavelengths between 100 Å and 600 Å. The target is a differentially-pumped gas cell which is viewed by a 2.2-meter grazing-incidence spectrometer. Our results show that the dominance of capture into the n=3 level observed at low velocity continues at higher velocity but that the relative importance of capture into n=4 increases at the higher velocity. We also see a marked increase in the relative population of the 3d level at higher velocity.

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e. Polarized Sodium Target
(R. W. Dunford, C. L. Liu, H. G. Berry, L. Young, N. B. Mansour, T. Dinneen*)

We have begun a program at the Argonne PII ECR ion source to study polarization transfer in collisions of highly-charged ions with a polarized sodium target. In addition to providing a new handle on the dynamics of ion-atom collisions, such studies will lead to the development of beams of ions with a high degree of nuclear and atomic polarization. As the first step in this program we have developed a sodium beam target. The use of a beam target has the advantage that it is easier to optically pump than a cell because of the reduced Doppler width. In addition, the target is more easily accessible for optical pumping, polarization measurement, observing the resonance florescence, and observing the radiation emitted after electron pick-up in ion-atom collisions (see Fig. IX-1).

The sodium oven is made up of a reservoir section and nozzle section. The nozzle consists of 9 holes which form a 2 mm x 2 mm array. Each hole is 200μ in diameter and 1 mm long. The nozzle is thermally isolated from the reservoir by a thin stainless tube. Separate heaters are used to maintain the nozzle section at 50° C above the reservoir section so that the long narrow holes do not clog. The sodium beam is collected on a liquid nitrogen cooled plate adjacent to the nozzle. Under normal operation the sodium beam is 5 mm in diameter in the center of the target chamber where the ion beam crosses it.

In the initial tests of the sodium target we measured state-selective electron capture. A normal incidence monochromator mounted on one side of the target chamber was used to measure photons coming from the interaction region between the ion beam and the sodium beam. An important feature seen in the spectra formed by collisions of O^{6+} on sodium is evidence for capture into higher excited states shown by the presence of transitions from n=4 to n=6, n=5 to n=7 and n=4 to n=7.

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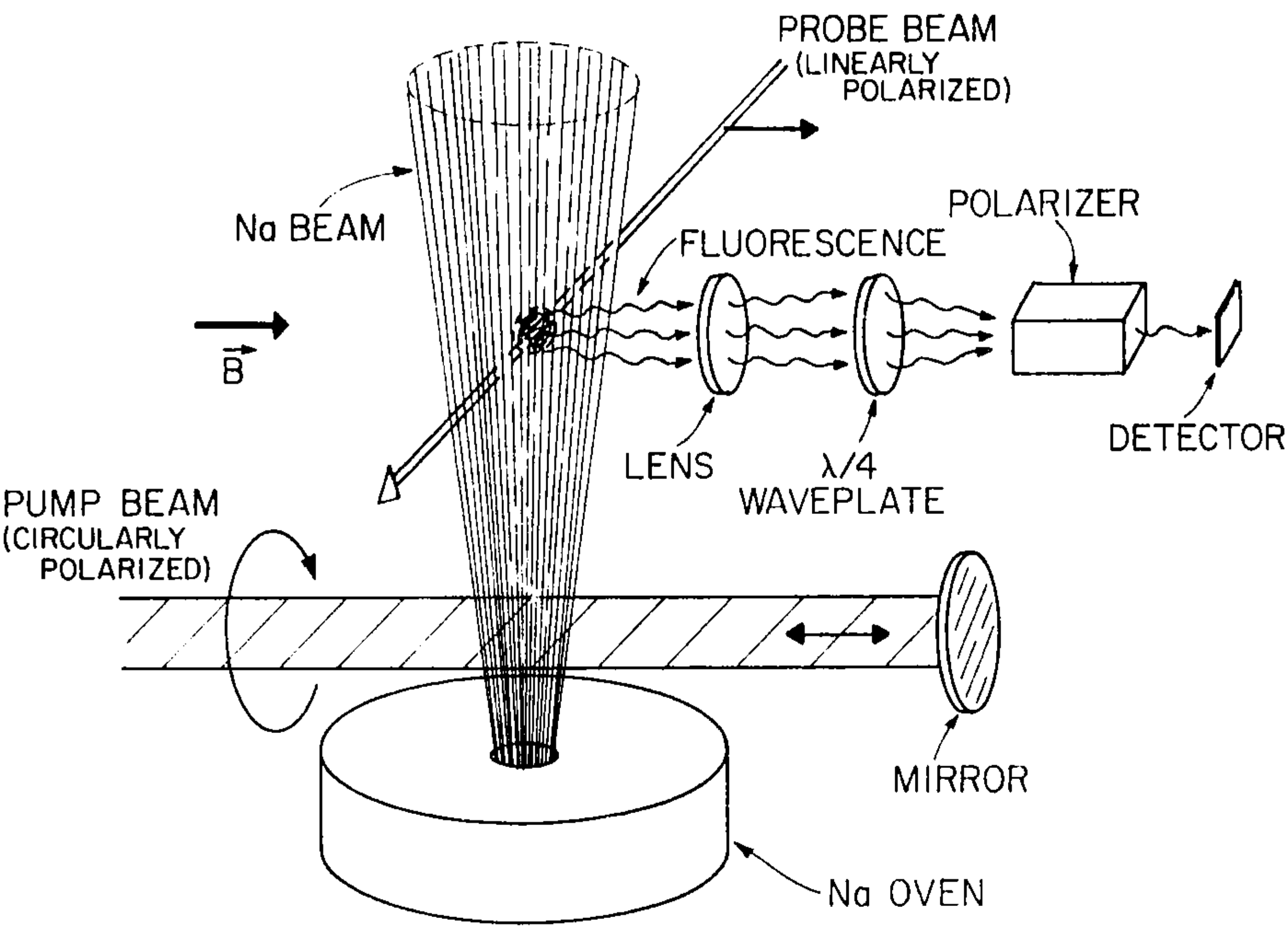

Fig. IX-1. The sodium atomic jet is intercepted by a circularly-polarized pump laser beam. The induced orientation is measured by a probe beam which produces circularly-polarized fluorescence at the same wavelength which is a direct increase of the orientation of the sodium atoms.

f. Photon Spectroscopy at the ECR Source
(M. L. A. Raphaelian,* H. G. Berry, L. Scudder and R. W. Dunford)

i) Oxygen 5+ on helium, 2-electron pickup cross sections

We are studying the relative probability of two-electron and one-electron pick-up in single collisions of slow, highly-charged ions on a helium gas target. We have made initial measurements using O^{5+} ions from the ECR source at energies varying from 100 keV to 1 MeV. At each energy, we measure the fluorescence spectrum in the wavelength range of 600 Å to 1200 Å at a series of different helium target pressures. We spectroscopically resolve and identify about 100 lines from oxygen charge states 2+ to 5+. The pressure dependence enables us to distinguish single collision, two-electron transfer from multiple collision effects. Work is in progress on analysis of the data.

ii) Silicon 11+ on helium, 1 and 2 electron pick-up.

We have obtained spectra in the range of 500 to 1200 Å from helium gas excitation of Si^{11+}. The spectra are rich and show strong two-electron pickup probabilities. We are analyzing the results as functions of the gas pressure. Initial measurements have been made at an ion energy of 700 keV. Further measurements will probe the velocity-dependence of the pick-up cross-sections.

iii) Doubly-excited sodium-like silicon, and other silicon spectroscopy.

In a beam-foil measurement using silicon 11+ ions from the ECR source at energies of 0.2 to 2 MeV, we have obtained spectra in the wavelength region near 900 Å. The large variation in beam velocity obtained from varying the terminal voltage of the ECR source platform enables us to identify the charge states of the emitting ions. These identifications are helpful in the work described above for the gas target (the greater intensity of the fluorescence from the foil source allows much higher spectral resolution.) In addition, we have identified the strongest transition in doubly-excited sodium-like silicon at 900 Å. This work is a continuation of our measurements in this sequence at lower energies. Further measurements should identify other transitions in this silicon ion. It will also be possible to study the aluminum spectrum once aluminum beams are available from the ECR source.

g. Electron Spectroscopy at the ECR Source

(H. G. Berry, M. L. A. Raphaelian,* T. Gay† and D. Schneider‡)

i) Saddle-point electrons - H, He, N, Ne on helium targets.

Previous measurements (in a collaboration at Rolla) showed the effect of "saddlepoint electrons" on the doubly-differential (angle and electron energy) electron pickup cross sections for protons and helium ions on helium targets. We have made initial experiments of a similar type using the Argonne ECR source. We are able to use strong beams of He^{++} and heavier ions, to obtain the charge-state dependence of the saddlepoint electron production. Initial measurements with He^{++} show some differences from the measurements at Rolla. Measurements using the heavier ions show low-energy Auger electron spectra which must be subtracted from the continua to compare the saddlepoint electron data. Further analysis is continuing.

ii) Doubly-differential cross sections of Si, and Ne on helium.

We have measured the Auger electron spectra produced from silicon, calcium and neon beams excited in a helium gas target as a function of electron emission angle, for several different ion beam energies. Initial analysis shows both electron pickup and excitation of the projectile ions. In the calcium case, all the lines are unclassified, and analysis is in progress elsewhere for the neon ions. An unexpected result is the ratio of the continuum contribution to the discrete line contributions to the electron spectra as a function of angle. The continuum fraction increases at larger scattering angles.

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(iii) Final-state interaction effects on Auger-line profiles

A few years ago at the Dynamitron, P. Arcuni measured a post-collision interaction (PCI) between doubly-excited helium target states with projectiles of multiply-charged lithium. The outgoing Auger electron from these states is attracted by the charged projectile ion as it leaves the target, leading to changes in the Auger electron spectral profiles. We can study these processes much more readily with the wide distribution of charge states available from the ECR source. The effect is much enhanced at low ion velocities. We have made initial measurements with He^{++} ions. Further measurements using carbon ions will continue.

iv) High-resolution Auger spectroscopy in neon - pickup and excitation Cross sections.

Auger electron measurements of Ne^{6+} and Ne^{8+} have been made using a double-electron spectrometer at zero degrees at 15q keV (q=charge state) energies at the Berkeley ECR source (Prior, Schneider et al.). We have continued this work at Argonne, going to higher projectile energies, maintaining the high resolution of the earlier work. Identification of the rich spectrum is in progress. This is aided particularly by the higher energy results where we observe a decrease in the electron pickup cross-sections balanced by a strong increase in the spectrum from direct excitation in the projectile system. These transitions are unobservable at the Berkeley ECR source energies. Analysis of the two collision mechanisms is continuing. Further measurements are projected with carbon, aluminum and calcium projectiles.

h. Electron Emission in Ne^{9+} + Ne Collisions
(R. Koch, S. Hagmann*, A. Gonzalez*, B. Krassig*, T. Quinteros*, H. Schmidt-Bocking†, A. Skutlartz†, H. G. Berry, R. W. Dunford, R. C. Pardo)

In a collaboration between Argonne, University of Frankfurt, and Kansas State University, the Ne^{9+} + Ne collision system was studied using a 2.5-MeV beam of Ne^{9+} ions produced by the ECR ion source and the high-voltage platform. The impact parameter dependence of X-ray production was measured for impact parameters up to three times the Ne K shell radius. The impact parameter dependence of electron production was also measured between 100 eV and 1400 eV. Two electron spectrometers were used providing measurements simultaneously at laboratory emission angles of 45 and 135 degrees. Each of the electron spectrometers was able to measure the azimuthal angle to $\pm 30°$. Preliminary analysis shows oscillations in the target K-Auger production probability associated with KK charge transfer as a function of impact parameter.

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i. Design Study for a Double-Orange Spectrometer
(R. W. Dunford, and K. E. Rehm)

An important future project at ATLAS is the investigation of unexplained positron peaks which have been observed in collisions of very heavy ions (e.g. U+Th, U+U, U+Ta) at the UNILAC accelerator at GSI, Darmstadt. The explanation of these peaks may require an understanding of the atomic physics associated with the highly-charged combined nucleus formed in the collision. The ATLAS experiments will utilize the uranium beams available after completion of the Uranium Upgrade. We have been investigating the use of a double-orange spectrometer for the ATLAS experiments. Compared to the existing double-orange spectrometer at GSI the new device would have improved efficiency, a clear signature for positron detection and better angular resolution.

Various spectrometer designs with and without a focal plane were investigated. The final design consists of two independent iron-free orange spectrometers. The entrance and exit field boundaries were chosen to obtain a large energy acceptance, minimize effects of the fringe field on the trajectories and to obtain a good determination of the polar angle theta from a measurement of energy and position using an array of Si detectors. The price for obtaining a good theta angular resolution (about 3 degrees for a position resolution of 2 cm) is the lack of a real focal plane. This type of spectrometer does not have the redundant energy information from the position measurement in the focal plane which is used effectively for background reduction in the GSI experiment. In order to obtain a clear signature for a positron being detected in the Si-array, a cylindrical BGO detector for detection of annihilation radiation would be used on the positron side of the spectrometer. The design also calls for a multi-wire proportional counter (MWPC) surrounding the Si- array which will provide a measurement of the azimuthal angle phi to $\pm$ 3 degrees. In all cases the angle resolution would not be limited by the detection device, but by the small-angle scattering in the target, which is estimated to be around 8 degrees for a 300 mg/cm^2 U target.

Extensive trajectory calculations for background electrons and positrons produced at various places in the spectrometer have been performed. The main sources for background are scattered gamma-rays which produce energy signals up to about 200 keV in the Si-detectors and delta-electrons scattered off the Cu-coils. The use of a multi-wire proportional counter should help reduce the gamma-background and also help distinquish the scattered electrons by a coarse track reconstruction with the use of the phi angle information from the MWPC and the Si array. This new spectrometer might also be useful in other atomic physics experiments where the scattering angles theta and phi of electrons and/or positrons have to be measured with good efficiency.

X. ATOMIC PHYSICS AT SYNCHROTRON LIGHT SOURCES

Atomic-physics studies of photoionization of heavy ions and atoms have recently been instigated by a group of researchers, principally from Texas A & M University (Professor David Church) and the University of Tennessee (Professor Ivan Sellin). Their initial work at the Stanford Synchrotron Radiation Laboratory resulted in the observations of highly-charged rare gas ions, for example Kr^{+9}, at very low recoil energies. This same group has now started experiments at the Brookhaven National Synchrotron Light Source (NSLS), in collaboration with a Brookhaven group (Dr. Keith Jones). We have arranged to participate in these experiments in the summer of 1989.

Since the recoil-ion energies correspond essentially to room temperatures or less, the work at NSLS is continuing with a program to trap the ions for subsequent secondary experiments. The Texas A & M group has previous experience in ion trap work, and has succeeded in trapping ions produced from heavy-ion impact. The photoionizing technique will produce much cooler ions initially (the initial temperatures are at least two orders of magnitude smaller), thus allowing much cleaner trapping geometries, and the cooling of more ions to very low temperatures.

Initial experiments last year at the NSLS have succeeded in trapping rare gas ions in a Penning trap with a well depth of 250 mV. These measurements already give approximate results for charge-changing collisions for the heavy ions. Relaxation times of the different charge states can lead to rate coefficients and then to cross sections, once the velocity distributions of the trapped ions have been determined.

Our collaboration with the group at the NSLS involved initial experiments in the summer of 1988, using Argonne National Laboratory discretionary funding, as a first step toward an atomic physics program at the APS at Argonne.

a. Stored Ion Research at the National Synchrotron Light Source
(Y. Azuma, H. G. Berry, D. A. Church*, M. Druetta†, B. Johnson‡, K. Jones‡, S. Kravis*, J. Levin§, M. Meron‡, and I. A. Sellin§)

Experiments on the X26-C beamline at the X-ray ring at the Brookhaven National Synchrotron Light Source took place in August, September and October, 1988. Prior to the runs, several new systems were installed and tested using the stored-ion trap built at Texas A & M. These included: a 1:1 focussing mirror for the synchrotron beam; a new light-beam chopper and drive; computer control of the experiment and the data collection; a "gas-puffer" system for introducing small gas loads to the trap; a new radial detection system of the stored ions; and improved cryopumping and sorption pumping of the entire target system.

The experiments involved the trapping of argon ions, and a study of the pressure dependence of the storage times for the different ion charge states. The results from the data analysis yielded (i) statistically improved rate coefficients for Ar^{3+}, Ar^{4+} and Ar^{5+} ions on argon, and new results for the rate coefficient of Ar^{6+} on argon. Some results are being analyzed for Ar^{2+} rate coefficients in argon. (ii) Photoionization of Ar^{2+} ion within the trap by the synchrotron photon beam. We studied the photo production of Ar^{5+} in this experiment. Only ion signals for charge states greater than 4+ were searched for. A background yield from other charge states was also detected and will be studied further.

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ACCELERATOR FACILITIES FOR ATOMIC PHYSICS

The atomic physics group is involved in experiments at four separate accelerator facilities - the ATLAS accelerator, the ECR (Electron Cyclotron Resonance) ion source, BLASE (Beam-Laser), and the Dynamitron. The first two facilities are primarily operated for nuclear physics experiments. However, there is significant atomic physics hardware involved in the beam lines, targets, and detector systems. The last two accelerators, BLASE and the Dynamitron, are dedicated primarily to our atomic physics program.

Our technical support staff, previously used to operate the Dynamitron, have become a support group for all atomic physics experiments on these accelerators. This makes possible much more efficient use of manpower, and facilitates the frequent changes in operation at the different experimental stations.

Our technical staff of four includes: B. J. Zabransky, a Mechanical Engineer who is in charge of design, technical improvements, and the set-up of experimental beam lines; R. L. Amrein and A. E. Ruthenberg are operators of the Dynamitron and work on technical projects at each of the other accelerators; C. Kurtz has primary responsibilities at BLASE and helps with maintenance and technical design at the other facilities. Kurtz and Zabransky also have responsibilities with individual experimental groups. Several temporary personnel have worked with the technical support group during the year.

Operations at ATLAS (R. W. Dunford, B. J. Zabransky, R. L. Amrein and A. E. Ruthenberg)

An atomic physics beam line was set up at the ATLAS heavy-ion accelerator in 1987. The beam line has two focussing regions separated by ten meters. A chamber containing an array of four silicon x-ray detectors and a movable foil target is located at the first focus. This apparatus has been used for coincidence measurements of the lifetimes of atomic states which decay by two-photon emission. A target chamber located at the second focus on the beamline is used with a grazing-incidence monochromator for precision spectroscopy of highly charged few-electron ions.

Atomic physics experiments aimed at studying ion-atom collisions have utilized other beam lines at ATLAS including the scattering chamber facility and the slit-pole magnetic spectrograph. The target chambers and detectors required for these experiments were installed immediately before the runs and removed afterwards.

The ECR Source Facility (R. W. Dunford, B. J. Zabransky, R. L. Amrein and A. E. Ruthenberg)

The ECR ion source which was built as part of the Uranium Upgrade of ATLAS was used extensively for atomic physics experiments in 1988 and the atomic physics staff became qualified operators of the source. Most of the experiments took advantage of the 350-kV high-voltage platform. While the ion source worked well, the isolation transformers powering the platform failed several times. Each failure necessitated the removal and replacement of the defective transformers.

ECR Source Beam lines for Atomic Physics (B. J. Zabransky, R. W. Dunford, M. L. A. Raphaelian and H. G. Berry)

A beam line for atomic physics experiments was initially set up in a temporary location adjacent to the ECR source. Last fall, this beam line was moved to a permanent location in a new building which was constructed as part of the ATLAS positive-ion-injector project. A switching magnet was installed in the ATLAS injection line to direct the beam into the atomic physics beam line. The first section of the beam line consists of focussing elements, steerers, slits and diagnostic elements which prepare the beam for the experimental section.

The first experimental section consists of up to three target chambers. The first chamber is used for ultraviolet spectroscopy. Either gas or foil targets are viewed by a 1-m normal-incidence monochrometer and a 2.2-m grazing-incidence monochromator. The second chamber contains a sodium-jet target which can be polarized by laser optical pumping. This target is used in experiments to study polarization transfer in ion-atom collisions. The final element in the beam line is a scattering chamber which is used for electron spectroscopy.

The BLASE Facility (L. Young, G. Berry, C. Kurtz, R. L. Amrein and A.E. Ruthenberg)

In the BLASE facility a fast ion beam is produced by an ion source, a stabilized 150-keV electrostatic accelerator, and a 90° analyzing magnet. The beam line is arranged for collinear interactions between the ion beam and a laser beam.

Technical upgrades in 1988 included a new water-cooling system for the lasers, the bending magnet and the diffusion pumps. A once-through system was replaced by a closed laboratory-supplied cooling system. This is expected to provide fewer problems with water corrosion.

A new microwave ion source was also developed in order to produce both multiply-charged ions and highly-excited metastable ions. This project is continuing at a small test-bench accelerator at the Dynamitron.

Operation of the Dynamitron Facility (R. L. Amrein, E. P. Kanter, A. E. Ruthenberg, and B. J. Zabransky)

The Dynamitron is a high-current, stabilized 5-MV accelerator which can provide singly-charged beams of most atomic ions and many molecular ions. It continues to be used primarily by the atomic physics program for work with fast molecular ions.

The program to study molecular-ion structures requires new ion sources to prepare molecules in well-defined initial states. We have investigated various schemes appropriate for sources of state-selected molecular ions in the Dynamitron high-voltage terminal. For example, several experiments have been carried out this year with molecular-ion beams produced by low-energy impact in the terminal. This was accomplished by modification of the electrode structure of a conventional duoplasmatron ion source. Several other schemes are under consideration for producing vibrationally-cold molecular ions.

Overall, the Dynamitron continued to perform well during the past year. It was shut down for a total of approximately 8 months spread over the year. During this time, the technical staff assisted in the construction of beam lines, small accelerators, ion sources, and accomplished machine modifications and repairs. The Dynamitron is now usually staffed 8 hours a day by two full-time staff, but can also be operated by experienced scientific personnel.

STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the permanent staff of the Physics Division for the year ending 31 March 1989. The program heading indicates only the individual's current primary activity.

EXPERIMENTAL NUCLEAR PHYSICS

Irshad Ahmad, Ph.D., University of California, 1966

*Jack Aron, B.S., Fenn College, 1955

Birger B. Back, Ph.D., University of Copenhagen, 1974

R. Russell Betts, Ph.D., University of Pennsylvania, 1972

†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

Donald F. Geesaman, Ph.D., State Univ. of New York, Stony Brook, 1976

§Bruce G. Glagola, Ph.D., University of Maryland, 1978

Roy J. Holt, Ph.D., Yale University, 1972

Harold E. Jackson, Jr., Ph.D., Cornell University, 1959

Robert V.F. Janssens, Ph.D. Univ. Catholique de Louvain, Belgium, 1978

Sheldon B. Kaufman, Ph.D., University of Chicago, 1953

Teng Lek Khoo, Ph.D., McMaster University, 1972

Dennis G. Kovar, Ph.D., Yale University, 1971

Walter Kutschera, Ph.D., University of Graz, Austria, 1965

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*Special Term Appointee.

†In charge of ATLAS operations and accelerator development.

‡Resident Associate Guest Appointee.

§ATLAS User Liaison Physicist.

*Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937
*James D. Larson, Ph.D., California Institute of Technology, 1965
*Frank J. Lynch, B.S., University of Chicago, 1944
Thomas Moog, B.A., Princeton University, 1975
†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
*G. Roy Ringo, Ph.D., University of Chicago, 1940
†Stephen J. Sanders, Ph.D., Yale University, 1977
‡John P. Schiffer, Ph.D., Yale University, 1954
Kenneth W. Shepard, Ph.D., Stanford University, 1970
§Silvia C. Tentindo Repond, Ph.D., University of Rome, 1979
*George E. Thomas, B.A., Illinois Wesleyan, 1943
Flemming Videbaek, Ph.D., University of Copenhagen, 1974
¶Lester C. Welch, Ph.D., University of Southern California, 1970
#Bruce D. Wilkins, Ph.D., University of California, 1962
*Jan L. Yntema, Ph.D., Free University of Amsterdam, 1952
Benjamin Zeidman, Ph.D., Washington University, 1957

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*Special Term Appointee.
†Left the Physics Division in December 1988.
‡Associate Director of the Physics Division. Joint appointment with the University of Chicago.
§Left the Physics Division in February 1989.
¶On assignment at DOE/HQ until October 1989.
#Transferred to EES Division in August 1988.

THEORETICAL NUCLEAR PHYSICS

*Arnold R. Bodmer, Ph.D., Manchester University, 1953
Richard R. Chasman, Ph.D., University of California 1959
Fritz Coester, Ph.D., University of Zurich, 1944
Henning Esbensen, Ph.D., University of Aarhus, 1977
†Dieter Kurath, Ph.D., University of Chicago, 1951
Stephen Landowne, Ph.D., Carnegie-Mellon University, 1970
Tsung-Shung Harry Lee, Ph.D., University of Pittsburgh, 1973
†James E. Monahan, Ph.D., St. Louis University, 1951
‡Vijay Pandharipande, Ph.D., University of Bombay, 1969
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

ATOMIC AND MOLECULAR PHYSICS

H. Gordon Berry, Ph.D., University of Wisconsin, 1967
William J. Childs, Ph.D., University of Michigan, 1956
Robert W. Dunford, Ph.D., University of Michigan, 1978
§Donald S. Gemmell, Ph.D., Australian National University, 1960
Elliot P. Kanter, Ph.D., Rutgers University, 1977
†Gilbert J. Perlow, Ph.D., University of Chicago, 1940
¶Zeev Vager, Ph.D. Weizmann Institute of Science, 1962
Linda Young, Ph.D., University of California, Berkeley, 1981

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*Resident Associate Guest Appointee from the University of Illinois, Chicago, Illinois.
†Resident Associate Guest Appointee.
‡Special Term Appointee from University of Illinois, Urbana, Illinois.
§Director of the Physics Division.
¶Joint appointment with Weizmann Institute of Science, Rehovot, Israel.

TECHNICAL AND ENGINEERING STAFF
(and areas of activity)

Ralph Benaroya (M.S. Case Institute, 1951)
Vacuum systems, magnets. Assigned to APS Division for FY1989.
Peter J. Billquist. ECR heavy-ion source.
John M. Bogaty (A.A.S. DeVry, 1961). Electrical-systems control.
Patric K. Den Hartog (B.S. Univ. Iowa, 1975). Operations Manager of ATLAS.
Joseph Falout (B.S.M.E. Univ. Illinois, 1970). Experimental equipment design.
Jack T. Goral (M.S.M.E. Wroclaw Institute, 1978). Experimental equipment design.
John P. Greene (M.S. DePaul, 1982). Target preparation.
Ray E. Harden (A.A.S. Milw. Sch. of Eng., 1957). ATLAS operation.
Dale J. Henderson (B.S. Elmhurst Coll., 1951). Detector development.
Donald V. Hulet. ATLAS operations. Transferred to EES Division in September 1988.
James M. Joswick (A.A.S. Milw. Sch. of Eng., 1964). Supervisor, ATLAS experimental equipment maintenance.
Raymond B. Kickert. Experimental equipment maintenance.
Robert Kowalczyk (M.S. Northeastern Ill. Univ., 1983). Technical assistance, medium-energy physics.
Charles A. Kurtz (M.S. Univ. Arkansas, 1984). Technical assistance, atomic physics.
Paul Markovich (B.S. Purdue, 1972). Surface chemistry, Executive Assistant for ATLAS upgrade.
Floyd H. Munson, Jr. (A.A.S. DeVry, 1966). ATLAS-control system.
Kirt Nakagawa (B.S. U. Illinois, 1988). ATLAS operations. Joined Physics Division in September 1988.
Bruce G. Nardi (A.A.S. DeVry, 1969). Supervisor, electronics maintenance; digital electronics design.
James E. Nelson (B.A. U. of Chicago, 1975). Technical assistance, medium-energy physics.
Ian R. Tilbrook (B.S. Penn. State U., 1987). ATLAS operation.
Philip R. Wilt (Johnstown Tech. Sch. 1973). Analog electronics design.
Bruce J. Zabransky (M.S. U. of Ill, Chicago, 1973). Supervisor of Dynamitron operation.
Gary P. Zinkann (B.S. DeVry, 1975). Superconducting resonators. ATLAS linac maintenance.

ADMINISTRATIVE STAFF

Allan Bernstein, M.B.A., Rosary College, 1986
*James R. Specht, A.A.S., DeVry Technical Institute, 1964

TEMPORARY APPOINTMENTS

Postdoctoral Appointees

Yoshiro Azuma (from University of Oregon, Eugene, Oregon):
Atomic and molecular studies.
(May 1988--)

Ali Belkacem (from University of Lyon, France):
Coulomb-explosion studies.
(September 1987--)

†Philippe L. Benet (from Purdue University, W. Lafayette, Indiana):
Heavy-ion research at ATLAS.
(December 1988 --)

Michael Carpenter (from Niels Bohr Institute, Roskilde, Denmark):
Heavy-ion research at ATLAS.
(February 1989--)

Ping-Lin Chung (from University of Iowa, Iowa City, Iowa):
Nuclear theory studies.
(October 1987--)

Kevin Coulter (from Princeton University, Princeton, New Jersey):
Medium energy studies.
(December 1988--)

Patricia B. Fernandez (from Univ. of Washington, Seattle, Washington):
Heavy-ion research at ATLAS.
(January 1989--)

Scott Fricke (from University of Minnesota, Minneaposis, Minnesota):
Nuclear theory studies.
(August 1988--)

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*Assistant Director of the Physics Division.
†Postdoctoral Appointee at Purdue University but resident at Argonne.

Brian K. Fujikawa (from Calif. Inst. of Technology, Pasadena, California):
Weak interactions studies.
(March 1989--)

Ronald Gilman (from University of Pennsylvania, Philadelphia, Pennsylvania):
Medium-energy pion and electron experiments.
(August 1986--)

Thomas Happ (from University of Frankfurt, W. Germany):
Heavy-ion research at ATLAS.
(January 1989--)

Edward R. Kinney (from Mass. Inst. of Technology, Cambridge, Mass.):
Medium-energy research.
(June 1988--)

Daniel Krakauer (from University of Maryland, College Park, Maryland):
Weak interaction studies.
(January 1989--)

Juergen Last (from University of Heidelberg, W. Germany):
Nuclear physics research at ATLAS.
(May 1988--)

Chia-jung Liu (from Yale University, New Haven, Connecticut):
Atomic physics at ATLAS.
(December 1987--)

Noura Mansour (from University of Virginia, Charlottesville, Virginia):
Accelerator-based atomic physics.
(May 1987--)

Claud Marchand (from University of Paris, France):
Medium-energy studies.
(September 1987--August 1988)

Eugene Moore (from Florida State University, Tallahassee, Florida):
Heavy-ion physics at ATLAS.
(January 1988--)

David H. Potterveld (from Calif. Inst. of Technology, Pasadena, Cal.):
Medium-energy physics research.
(July 1988--)

Charles Price (from Indiana University, Bloomington, Indiana):
Relativistic quantum-field theory.
(October 1986--July 1988)

*Gabriele Rathke (from University of Mainz, W. Germany):
Heavy-ion research at ATLAS.
(July 1987--August 1988)

Tzu-Fang Wang (from Yale University, New Haven, Connecticut):
Heavy-ion research at ATLAS.
(February 1986--December 1988)

†Frank L. H. Wolfs (from University of Chicago, Chicago, Illinois):
Heavy-ion research at ATLAS.
(June 1987--)

Long-Term Visitors (at Argonne more than 4 months)

‡R. Stephen Berry (University of Chicago, Chicago, Illinois):
Atomic theory.
Part-time appointment.

§David A. Church (Texas A & M University, College Station, Texas):
Atomic physics studies. (January 1989--)

¶Zbigniew Grabowski (Purdue University, W. Lafayette, Indiana):
Heavy-ion research at ATLAS.
(July 1988--December 1988)

Michael Hass (Weizmann Institute of Science, Rehovoth, Israel):
Molecular-ion studies; heavy-ion research at ATLAS.
(August 1987--August 1988)

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*Feodor Lynen Postdoctoral Fellowship from Alexander von Humboldt Foundation.

†Enrico Fermi Scholar.

‡Joint Appointment.

§Faculty Research Leave Participant.

¶Faculty Research Participant.

Hans J. Körner (Technical University of Munich, W. Germany):
Heavy-ion research at ATLAS.
(August 1987--August 1988)

Harry J. Lipkin (Weizmann Institute of Science, Rehovot, Israel):
Investigation of current problems in hadron spectroscopy.
(May 1988--August 1988)

Jonhson F. Ordonez (University of Sao Paulo, Brazil):
ATLAS development and construction.
(February 1989--)

*Peter Sigmund (Odense University, Osense, Denmark):
Particle penetration phenomena.
(September 1988--)

Juan Jaime Vega (from Institute Nacional de Investigaciones, Mexico City, Mexico):
FMA development and construction.
(January 1989--)

Resident Graduate Students

David T. Baran (Northwestern University, Evanston, Illinois):
Medium-energy nuclear physics studies. (June 1985--)

Timothy Dinneen (University of Chicago, Chicago, Illinois):
Laser spectroscopy of fast ions. (November 1986--)

Christopher Fasano (University of Chicago, Chicago, Illinois):
Quark effects in nuclei. (October 1985--October 1988)

Jeffrey Hangst (University of Chicago, Chicago, Illinois):
Ordered ion beams. (November 1988--)

Michael A. Kroupa (University of Chicago, Chicago, Illinois):
Search for magnetic monopoles using a plastic scintillator array.
(July 1982--)

Zhengtian Lu (University of Chicago, Chicago, Illinois):
Nuclear theory studies. (October 1988--)

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*1988-89 Argonne Fellow.

Ross E. Mitchell (University of Chicago, Chicago, Illinois): Study of the stereochemical structure of small polyatomic molecular ions by the "Coulomb-expolsion" method. (February 1988--)

Mark L. Raphaelian (University of Illinois at Chicago, Illinois): Accelerator-based atomic physics. (January 1987--)

Danshao Ye (University of Notre Dame, Notre, Indiana): Heavy-ion research at ATLAS. (February 1989 --)

Short-Term Visitors (at Argonne less than 4 months)

A. Faculty

*Patrick J. Cooney (Millersville University, Millersville, Pennsylvania): Molecular-ion studies. (June--August 1988)

*Babek Etemadi (Florida A & M University, Tallahassee, Florida): Weak interaction studies. (May--August 1988)

Walter Glöckle (Ruhr University, Bochum, W. Germany): Nuclear theory studies. (September--November 1988)

Dietrich Habs (Max-Planck-Institut, Heidelberg, W. Germany): Heavy-ion research at ATLAS. (March--May 1988)

†Edward L. Hohman (York Community High School, Elmhurst, Illinois): Summer high-school student coordinator. (June--August 1988)

Robert Koch (J. W. Goethe University, Frankfurt, W. Germany): Atomic physics at ATLAS. (May--June 1988)

*Charles Maguire (Vanderbilt University, Nashville, Tennessee): Heavy-ion research at ATLAS. (June--August 1988)

Michael Paul (Hebrew University, Jerusalem, Israel): Heavy-ion research at ATLAS. (September--October 1988)

*Francis Prosser (University of Kansas, Lawrence, Kansas): Heavy-ion research at ATLAS. (May--July 1988)

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*Faculty Research Leave Participant.

†Guest Faculty Research Participant.

*Akunuri Ramayya (Vanderbilt University, Nashville, Tennessee): Heavy-ion research at ATLAS. (June--August 1988)

*Daniel Schlensker (Concordia College, River Forest, Illinois): Development of 2-MeV Van de Graaff. (June--August 1988)

*Timothy Steimle (Arizona State University, Tempe, Arizona): Atomic physics studies. (August 1988)

*Leonard B. Weisenthal (Lewis University, Romeoville, Illinois): Development of 2-MeV Van de Graaff. (June--August 1988)

*William R. Wharton (Wheaton College, Wheaton, Illinois): Development of 2-MeV Van de Graaff. (June--August 1988)

B. Graduate Students

†David Klepacki (University of Chicago, Chicago, Illinois): Heavy-ion research at ATLAS. (September 1988--)

†Madhusree Mukerjee (University of Chicago, Chicago, Illinois): Nuclear theory research. (September 1987--)

†Thih-Yuen Tung (Northwestern University, Evanston, Illinois): Nuclear physics experiments. (September 1987--)

†Zhou Yu (Northwestern University, Evanston, Illinois): Intermediate-energy physics. (September 1987--)

Undergraduate Students

Bryan Affolter (DeVry Institute of Technology)
Robert Bleicher (North-Central College)
Laura Budrik (Illinois Benedictine College)
Daniel Burns (Lewis University)
William Buttler (University of Texas)

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*Faculty Research Participant.

†Guest Graduate Student

Jay Dawson (Carnegie-Mellon University)
Stewart DeSoto (Wheaton College)
Joseph Dey (Washington University)
James Done (Roosevelt University)
Douglas Dunston (Harvey Mudd College)
Richard Ellmaker (Millersville University)
Paul Glezen (University of Arkansas)
Scooter Haase (E. New Mexico University)
Gur Hoshen (Stanford University)
Eric Johnson (Lewis University)
Robert Koch (J. W. Goethe University, Frankfurt)
Raymond Konopka (Illinois Benedictine College)
Mark Kopciewski (University of Illinois at Chicago)
Alfred Kraxenberger (Technical University of Munich)
Tina LaGesse (Lewis University)
Christopher Legan (Northern Illinois University)
Kenneth Luther (Mount Union College)
James Magee (Northern Arizona University)
Chad Moore (Bloomsburg University)
Patrick Morton (North-Central College)
Gregory Perschbacher (College of St. Francis)
Bonnie Pewitt (University of Kentucky)
Christopher Phelps (Middlebury College)
Robert Rafac (University of Chicago)
Loren St. Clair (Kalamazoo College)
Michael Salisbury (North-Central College)
Lance Scudder (University of Oklahoma)
Christopher Shaffer (Hope College)
Craig Sorrie (Wheaton College)
Brett Stevens (University of Chicago)
Jason Stott (Northwestern University)
Phillip Strickhorn (DeVry Institute of Technology)
Jennifer Sundberg (Bowling Green State University)
Richard Vondrasek (University of Chicago)
Greg Wiemerslage (Elmhurst College)

Pre-College Program (Just Graduated from High School)
(June--August 1988)

Matthew Marjanovic (Oak Park-River Forest High School)
Douglas E. Smith (Bolingbrook High School)
Brett Stevens (Naperville Central High School)

HIGH SCHOOL STUDENT AIDES
(June--July 1988)

James Douglass (Glenbard North High School)
Christopher Dunn (York Community High School)
Henry Liu (Lane Technical High School)
Peter Pashigian (University of Chicago Laboratory High School)
Kenneth Wharton (Wheaton North High School)
Sharon Wickboldt (Morton High School West)

PUBLICATIONS FROM 1 APRIL 1988 THROUGH 31 MARCH 1989

This 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 tests in volumes of proceedings; they are listed chronologically.

JOURNAL ARTICLES AND BOOK CHAPTERS

rf Properties of an Oxide-Superconductor Half-Wave Resonant Line
J. R. Delayen, K. C. Goretta, R. B. Poeppel, and K. W. Shepard
Appl. Phys. Lett. 52, 930 (1988)

Incomplete Fusion Reactions Induced by ^{12}C at 5.5-10 MeV/Nucleon
I. Tserruya, V. Steiner, Z. Fraenkel, P. Jacobs, D. G. Kovar, W. Henning, M. F. Vineyard, and B. G. Glagola
Phys. Rev. Lett. 60, 14 (1988)

Transition from Quasi-Elastic to Deep-Inelastic Reactions in the $^{48}Ti+^{208}Pb$ System
K. E. Rehm, A. M. van den Berg, J. J. Kolata, D. G. Kovar, W. Kutschera, G. Rosner, G. S. F. Stephans, and J. L. Yntema
Phys. Rev. C 37, 2629 (1988)

Structural Changes Along and Above the Yrast Line of ^{154}Dy
W. C. Ma, M. A. Quader, H. Emling, T. L. Khoo, I. Ahmad, P. J. Daly, B. K. Dichter, M. Drigert, U. Garg, Z. W. Grabowski, R. Holzmann, R. V. F. Janssens, M. Piiparinen, W. H. Trzaska and T.-F. Wang
Phys. Rev. Lett. 61. 46 (1988)

A Superdeformed Band in ^{151}Dy
G.-E. Rathke, R. V. F. Janssens, M. W. Drigert, I. Ahmad, K. Beard, R. R. Chasman, U. Garg, M. Hass, T. L. Khoo, H.-J. Korner, W. C. Ma, S. Pilotte, P. Taras and F. L. H. Wolfs
Phys. Lett. B 209, 177 (1988)

Absolute Energy Measurement of Heavy Ion Beams Using a Resonant Time-of-Flight System
R. Pardo, B. E. Clifft, P. DenHartog, D. Kovar, W. Kutschera, and K. E. Rehm
Nucl. Instrum. Methods A270, 226 (1988)

K-Shell Fluorescent Yields in Highly Stripped ^{57}Fe Atoms
W. R. Phillips, K. E. Rehm, W. Henning, I. Ahmad, J. P. Schiffer, B. Glagola, and T. F. Wang
J. de Physique C9, 311 (1987)

Programming Style: An Example
L. C. Welch
Computers in Physics, Sept.-Oct., 65-75 (1988)

Superconducting rf Cavity in a dc Magnetic Field
R. Benaroya and K. W. Shepard
Rev. Sci. Instrum. 59, 2100 (1988)

Layered Structure in Condensed, Cold One-Component Plasmas Confined in External Fields
John P. Schiffer
Phys. Rev. Lett. 61, 1843 (1988)

Reply to Comment by Shapira
S. J. Sanders, D. G. Kovar, B. B. Back, C. Beck, B. K. Dichter, D. Henderson, R. V. F. Janssens, J. G. Keller, S. Kaufman, T. F. Wang, B. Wilkins, F. Videbaek
Phys. Rev. Lett. 61, 2154 (1988)

Feasibility of a Crystalline Condensed State in Cooled Ion Beams of a Storage Ring
John P. Schiffer and Aneesur Rahman
Z. Phys. A - Atomic Nuclei 331, 71 (1988)

A Focal Plane Detector for Reactions with Medium-Weight Projectiles
K. E. Rehm and F. L. H. Wolfs
Nucl. Instrum. Methods A273, 262 (1988)

^{48}Ti + ^{104}Ru Single-Nucleon Transfer at the Barrier
S. J. Sanders, B. B. Back, R. R. Betts, D. Henderson, R. V. F. Janssens, K. E. Rehm and F. Videbaek
Phys. Rev. C37, 1318 (1988)

Levels in ^{110}Pd, ^{112}Pd, ^{114}Pd, and ^{116}Pd from the Beta Decays of the On-Line Mass-Separated Rh Isotopes
J. Aysto, C. N. Davids, J. Hattula, J. Honkanen, K. Honkanen, P. Jauho, R. Julin S. Juutinen, J. Kumpulainen, T. Lonnroth, A. Pakkanen, A. Possoja, H. Penttila, P. Taskinen, E. Verho, A. Virtanen, and M. Yoshii
Nucl. Phys. A480, 104 (1988)

Half-Life Measurements for Neutron-Rich Tc, Ru, Rhj, and Pd Isotopes. Identifiction of the New Isotopes ^{111}Tc, ^{113}Ru, and ^{113}Rh
H. Pentilla, P. Taskinen, P. Jauho, V. Koponen, C. N. Davids, and J. Aysto
Phys. Rev. C 38, 931 (1988)

The Superconducting Neutron Decay Spectrometer PERKEO
P. Bopp, E. Klemt, J. Last, H. Schutze, D. Dubbers, and S. J. Freedman
Nucl. Instrum. Methods A267, 436 (1988)

Pulsed-Beam Neutron-Lifetime Measurement
J. Last, M. Arnold, J. Dohner, D. Dubbers, and S. J. Freedman
Phys. Rev. Lett. 60, 995 (1988)

Limits on Fractionally-Charged Particle Production from Cosmic Rays and Accelerators: How Near Zero?
S. J. Freedman and J. Napolitano
Near Zero: New Frontiers of Physics, eds. J. D. Fairbank, B. S. Deaver, Jr., C. W. F. Everitt, P. F. Michelson (W. H. Freeman and Company, NY 1988) pp. 500-510

Inelastic Scattering of Pions by ^{10}B
B. Zeidman, D. F. Geesaman, P. Zupranski, R. E. Segel, G. C. Morrison, C. Olmer, G. R. Burleson, S. Greene, R. L. Boudrie, C. L. Morris, L. W. Swenson, G. S. Blanpied, B. G. Ritchie, C. L. Harvey Johnstone
Phys. Rev. C 38, 2251 (1988)

Pair Decay of the 2.2-MeV Excited State of the Deuteron: Limits on Light-Particle Emission
J. Dohner, J. Last, M. Arnold, S. J. Freedman, D. Dubbers
Phys. Rev. D 38, 2722 (1988)

Measurement of the Differential Cross Section for the Reaction $^4H(\gamma,p)n$ at High Photon Energies and $\theta_{cm} = 90^o$
J. Napolitano, S. J. Freedman, D. F. Geesaman, R. Gilman, M. C. Green, R. J. Holt, H. E. Jackson, R. Kowalczyk, C. Marchand, J. Nelson, B. Zeidman, D. G. Boyd. D. Collins, B. W. Filippone, J. Jourdan, R. D. McKeown, R. Milner, D. Potterveld, R. Walker, C. Woodward, R. E. Segel, Y.-Y. Tung, P. E. Bosted, E. Kinney, Z.-E. Meziani, R. Minehart
Phys. Rev. Lett. 61, 2530 (1988)

Energy Dependence of the Beta Asymmetry in the Decay of 8Li
J. R. Hall, D. L. Clark, S. J. Freedman and S. S. Hanna
Nucl. Phys. A483, 1 (1988)

Beta-Decay Asymmetry of the Neutron
E. Klemt, P. Bopp, L. Hornig, J. Last, S. J. Freedman, D. Dubbers and O. Scharpf
Z. Phys. C 37, 179 (1988)

Δ Electroproduction and Inelastic Charge Scattering from Carbon and Iron
D. T. Baran, B. F. Filippone, D. Geesaman, M. Green, R. J. Holt, H. E. Jackson, J. Jourdan, R. D. McKeown, R. G. Milner, J. Morgenstern, D. H. Potteerveld, R. E. Segel, P. Seidl, R. C. Walker, and B. Zeidman
Phys. Rev. Lett. 61, 400 (1988)

Limits on $\nu_\mu \to \nu_e$ Oscillations
L. S. Kurkin, R. W. Harper, T. Y. Ling, J. W. Mitchell, T. A. Romanowski, E. S. Smith, M. Tinko, S. J. Freedman, J. Napolitano, B. K. Fujikawa, R. M. McKeown, K. T. Lesko, W. C. Choi, A. Fazley, R. L. Imlay, W. J. Metcalf, R. D. Carlini, J. B. Donahue, G. T. Garvey, and V. D. Sandberg
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