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Donald S. Gemmell
Division Director

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Edited by Karen J. Thayer

FOREWORD

The past year has seen several major accomplishments within the Argonne Physics Division. Perhaps foremost among these is the successful completion and testing of the second stage of construction of the new positive-ion injector for ATLAS. On April 25, 1990 a ^{86}Kr beam was successfully accelerated for the first time through the enlarged (but not yet complete) version of the new superconducting injector linac that couples an ECR ion source to ATLAS. Ten resonators, housed in two large cryostats, provided a total accelerating voltage of 7 MV, about 60% of the 12 MV expected from the final 18-resonator injector linac. As a test of all aspects of the new injector system, a beam of $^{86}Kr^{15+}$ from the ECR source was accelerated through ATLAS and used in a nuclear physics experiment at the Enge split-pole spectrograph. The systems ^{86}Kr+^{92}Mo and ^{86}Kr+^{54}Fe were studied at beam energies up to 400 MeV. The beam current on target was 4 pnA after passing through a 1 x 3 mm collimator system. The beam quality was excellent with a phase-space area $\Delta E \cdot \Delta t$ of only 75 keV-ns (both ΔE and Δt being FWHM). This value is much smaller than any obtained previously for ions in the same mass range from the tandem injector. No beam contaminants of other isotopes or elements could be detected. During a 5-day run the beam intensity was very stable and the ^{86}Kr consumption rate in the ECR source was about 1.2 mg/hr. Following this initial test, the accelerating voltage of the injector linac is being increased to 8 MV. These successes, coupled with the demonstration last year of our capability for producing from the ECR source intense, stable, highly-charged beams of uranium ions, provide ample "proof-of-principle" for the new positive-ion injector and lead us to be very confident about the successful completion of the "uranium upgrade" which involves the addition of a third cryostat and which is scheduled for completion in early 1991.

Further advances are being achieved in major equipment projects associated with ATLAS. The Fragment Mass Analyzer (FMA) is now well along the road to completion. The magnetic components have been installed on the rotatable support structure and the electrostatic dipoles have been successfully tested up to 500-kV gap voltage (the design objective is 450 kV). Experiments are expected to start with the FMA towards the end of 1990. APEX (ATLAS Positron Experiment) is a major collaboration involving scientific and support personnel from Argonne, Michigan State University, Yale University, the University of Rochester, Princeton University, Florida State University, and the University of Washington. It is designed to observe and elucidate the anomalous positron peaks that have been observed at GSI over the past few years and whose origins are as yet unexplained. The collaboration submitted a successful proposal to the Department of Energy in 1989. Construction of the apparatus, which involves a large solenoidal spectrometer, is now well underway and completion is expected to coincide closely with the achievement at ATLAS of energetic beams of the very heavy elements that appear to be necessary to observe these positron peaks.

We at Argonne are major participants in the GAMMASPHERE project for which construction is expected to start in FY1991. This approximately $20M instrument will consist of an assembly of over 100 Compton-suppressed germanium spectrometers and is expected to make a major contribution to our further understanding of high-spin phenomena and various other areas in nuclear physics. The project is a broadly-based one having support from several laboratories. Argonne has made significant contributions already and has taken the primary responsibility for the development and testing of prototype detectors.

A further recent development related to ATLAS is the initiation of a program of basic studies in rf superconductivity. Our efforts in this area have, until recently, been overwhelmingly directed towards the goal of designing and constructing the ATLAS accelerator. This new program will focus on careful studies of the basic physics involved in rf-superconducting structures and try to elucidate factors that currently impose limitations on their performance.

A noteworthy achievement during this past year was the demonstration of very high surface electric fields in tests of a superconducting RF-quadrupole device. These experiments were performed collaboratively with the Argonne Engineering Physics Division and reached fields more than a factor of two higher than so far reported for normally conducting RFQ structures. The result indicates that superconducting RF technology may provide a new range of options for RFQ design.

ATLAS supports a broadly-based and diverse experimental program. Demand for beam time at the facility continues to grow as our user community expands. Because of funding constraints, the operation of ATLAS is limited to 5-1/2 days/week.

A large fraction of ATLAS research is devoted to gamma-ray experiments. Of particular interest is the recent work on superdeformation in the mass-190 region where evidence has now been found indicating that superdeformation persists down to very low spins.

Research in our nuclear theory group has many close connections with the experimental programs at ATLAS and in medium-energy physics. An active program of theory visitors has been expanded with the help of Laboratory discretionary funding.

The Physics Division ran several workshops and conferences during the past year. Of particular note were the "Symposium on the Occasion of the 40th Anniversary of the Nuclear Shell Model" (May 25-27, 1989), the "Workshop on the Interface between Nuclear Structure and Heavy-ion Reaction Dynamics" (held at the University of Notre Dame, May 24-26, 1990--a meeting jointly sponsored and organized by ANL and Notre Dame), and the "Workshop on Atomic Physics at the Advanced Photon Source", March 29-30, 1990.

During the Shell-Model Symposium, a plaque honoring Maria Goeppert Mayer was unveiled at the front of the Physics building. The modern nuclear shell model was conceived in 1949 by Dr. Mayer, who was then on the staff at Argonne, and independently in Germany by J. Hans D. Jensen, Otto Haxel, and Hans E. Suess. The Laboratory also used the occasion to announce a new initiative, the Maria Goepper Mayer Distinguished Scholar Program, with the goal of attracting outstanding women scientists to Argonne.

In atomic physics our staff has continued to exploit the unique opportunities offered by major facilities located at Argonne; e.g. ATLAS (and its new ECR ion source on a high-voltage platform), the 5-MV Dynamitron, and the highly stable ion-beam/laser facility, BLASE. Our attention is progressively turning also to the opportunities that will be presented by the 7-GeV Advanced Photon Source now under construction at Argonne. Supported by Laboratory discretionary funds, a modest effort has been started in atomic physics studies with existing light sources and we have participated with other ANL Divisions in proposing the creation of a BES Synchrotron Radiation Center at the APS.

Our medium-energy physics staff is heavily involved in preparations for the experimental program at CEBAF. We are authors or co-authors of several proposals for experiments and in addition, several staff members are involved in advisory capacities at CEBAF. We expect to assume the responsibility for building a short-orbit spectrometer for experiments in Hall "C" that will involve the production of short-lived hadrons. While eagerly awaiting the chance to perform experiments at CEBAF (scheduled to start in 1994) our staff is engaged in a variety of current or planned experiments with energetic lepton beams (e.g. at FNAL, Saclay, Novosibirsk, and HERA) all of which have as a common theme the study of the internal structure of the nucleon and especially those aspects that play a role in shaping the character of nuclear forces.

An active program also continues in the study of weak interactions at low energies. The principal aim here is to make tests of the "standard model" as well as to search for phenomena that signal physics beyond our present understanding. The work includes participation in the LAMPF experiment (E645) searching for neutrino oscillations, participation in the Cygnus group at Los Alamos studying cosmic-ray point sources, measurements on free-neutron beta decay at the Institute Laue-Langevin, and a variety of measurements using low-energy facilities at Argonne and elsewhere.

The ANL Physics Division responded vigorously following reports purporting to observe "cold fusion". Several ingenious experiments were designed and performed--all with negative results. However, this brief but exciting interlude left plenty of evidence that creative and imaginative experimental physics is alive and well as a science at Argonne National Laboratory.

During February 1990, the Physics Division was honored by a visit from Admiral James D. Watkins, Secretary of Energy. Admiral Watkins displayed a keen interest in ATLAS and its research programs, and also in the Division's contributions to the education of young scientists.

Donald S. Gemmell
Director, Physics Division

July 1990

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I. RESEARCH AT ATLAS

The heavy-ion research program at the Argonne Physics Division concentrates on experiments performed at the heavy-ion accelerator ATLAS. ATLAS in its present stage allows the acceleration of ions in the mass range $3 \lesssim A \lesssim 100$ to energies of about 20 MeV/u (depending on the ion species). This energy range covers the region from the Coulomb barrier where single-particle effects dominate, up to the region where complex multi-particle reactions occur. In comparison to other accelerators, ATLAS allows for easy energy variability and has beam characteristics (emittance, duty cycle and timing properties) that are of very high quality. An upgrading program is presently under way which increases the beam intensity and mass range of beams to all nuclear species. ATLAS is a National User Facility with its research time allocated by a Program Advisory Committee.

The effort of the research staff associated with ATLAS is distributed between on-going research and the planning, design, and testing of new equipment for future experiments. Outside users are involved in many of these projects. About 70% of all experiments include participants from outside ANL. The largest new project, the ATLAS positron-electron experiment (APEX), is a joint venture of six institutions.

Because of the versatility of ATLAS the research program covers a wide range of experiments ranging from Coulomb excitation to the study of complex rearrangement reactions.

A large fraction of the effort last year was devoted to γ-ray experiments. Based on cranked shell-model calculations performed by our theory group, the existence of a new region of superdeformation (SD) in the mass-190 region was predicted. Since the first observation of SD in ^{191}Hg last year, considerable progress has been made. Evidence for SD has now been found in the neighboring nuclei ^{190}Hg and ^{192}Hg, and in ^{191}Hg two additional excited superdeformed bands were discovered. In contrast to the A=150 region, these bands in the Hg isotopes were found to extend to much lower rotational frequencies indicating that SD persists to very low spins. First experiments to search for octupole shapes concentrated on a new region of octupole deformation around ^{146}Ba which was discovered some years ago. Since nuclei in this mass region cannot be formed with usual in-beam techniques, γ-γ coincidence techniques using a ^{248}Cf fission source were employed. It was found that, contrary to theoretical predictions, ^{142}Xe showed no signatures of octupole deformation. The same experiments also provided new spectroscopic information about very neutron-rich Zr-isotopes with masses A=100-104.

The study of heavy-ion-induced transfer reactions covers a wide field ranging from simple one-nucleon exchange to complex deep-inelastic reactions. Investigations of these processes at energies close to the barrier represents a very important area of research, since better understanding of these fundamental processes has a bearing on most other reaction modes. Because of the many states involved, heavy-ion-induced quasi-elastic few-nucleon transfer reactions are found to have large cross sections. Consequently these reactions can have a strong influence on other channels, such as elastic scattering or fusion reactions. For the strength of the one- and two-neutron transfer reactions a systematic picture has evolved which is based on simple classical matching conditions, with one-neutron transfer reactions larger by a factor of four than the corresponding two-neutron transfers. In an extension of these systematics to proton transfer, it was found that the cross section ratio between one- and two-proton transfer is only about 2:1, pointing to a possible enhancement of two-proton transfer. The behavior of transfer reactions at large distances also showed some unexpected results. Contrary to the predictions from semiclassical tunneling theories the falloff of the cross section as a function of the distance was found to be energy- and nuclear-structure dependent.

Studies of more complex rearrangement reactions, such as fusion followed by fission at bombarding energies close to the barrier, also produced some unexpected results. Angular anisotropies for ^{12}C- and ^{16}O-induced fission reactions in the actinides pointed to unusually large angular momenta associated with these processes. In order to eliminate the contributions from sequential fission, an experiment using time-of-flight techniques has been performed. It appears that the exclusion of sequential fission events reduces the angular anisotropy somewhat, but the main discrepancy in the ℓ-distribution for these reactions still remains.

Considerable effort went into studies of angular-momentum-bearing modes of a di-nuclear system excited either in compound fission or fission-like reactions. It was found that conventional statistical models were unable to explain features of the twisting, bending and wriggling mode observed in the experiments.

The program on accelerator mass spectrometry (AMS) is currently in transition from tandem-based experiments to new experiments with the ECR source. In a series of experiments it was shown that ^{41}Ca detection at natural levels in minerals and bones can be performed without any pre-enrichment. The main effort in this field concentrated on interpreting the data obtained so far, in particular to what extent ^{41}Ca is produced by various processes, such as neutron capture, spallation and α- or ^{3}He-induced reactions. A first exploratory experiment using the ECR source has been performed for AMS studies with ^{39}Ar.

Some experiments performed at ATLAS are at the borderline to atomic physics. The charge-state dependence of internal conversion and fluorescence yields has been investigated for the case of ^{57}Fe and experiments with ^{83}Kr are planned for the future. Experiments on dielectronic recombination of channeled ^{48}Ti ions have been performed. The resonance widths for dielectronic recombination were almost an order-of-magnitude smaller than in previous experiments. This result shows that crystalline targets can provide a close approximation to a free-electron gas.

In the area of astrophysics an experiment measuring the γ-width of the first excited state in ^{14}O has been completed. This experimental result is an important input parameter for the hot CNO cycle in stellar nucleo-synthesis calculations.

Extensive calculations have been performed to study properties of cooled ions which are contained in traps or storage rings. In particular the normal modes and the effect of shear forces have been investigated. First tests with cooled proton beams at the IUCF storage ring have begun.

Two major new experimental stations will become operational in the near future. The fragment mass analyzer (FMA) is scheduled for completion in the summer of 1990. The support frame has been installed and the construction of the ion-optical elements is near completion. The beam-transport system is presently being installed. This device will allow new classes of experiments in the field of spectroscopy of exotic nuclei outside the valley of stability.

Considerable effort has been devoted to the design and development of equipment needed for the ATLAS positron-electron experiment (APEX). In collaboration with several university groups a new apparatus has been designed to study the mysterious peaks found in electron-positron coincidences in collisions between two very heavy nuclei. The new design, a large solenoidal spectrometer, has high efficiency and by a measurement of the emission angles of electrons and positrons, also allows for a determination of the invariant mass of a hypothetical decaying object.

In connection with the GAMMASPHERE project some tests of large Ge-detectors and BGO anti-Compton shields have been performed. We expect to play a leading role in the final design of the complete suppressed Ge-module. First tests to improve the resolution of Ge-detectors via software corrections have also been started.

A. QUASIELASTIC PROCESSES AND STRONGLY-DAMPED COLLISIONS

The main goals of the quasi-elastic reaction studies are (a) to improve our understanding of nucleon transfer processes ranging from simple one-particle transfer reactions to complex deep-inelastic multi-particle transfer processes and (b) to study the influence of quasi-elastic reactions on other reaction modes. By choosing specific target-projectile combinations and varying the bombarding energy it is possible to study the influence of nuclear structure in these heavy-ion reactions in greater detail. ATLAS, with its easy energy variability, is the ideal accelerator to study these processes from low bombarding energies, where the Coulomb potential dominates up to energies above the barrier where the nuclear potential is important. As a detector system, the split-pole spectrograph with its focal-plane detector has been used for most of these studies. In its present configuration it allows the separation of individual isotopes and elements up to about the mass-100 region. In some of the experiments particle identification was obtained from characteristic γ rays using the Argonne-Notre Dame BGO ball.

In a series of experiments performed at bombarding energies in the vicinity of the Coulomb barrier, it was observed that quasi-elastic reactions can strongly influence other reaction channels (e.g. elastic scattering and fusion). A detailed understanding of these correlations between the various reaction modes involves systematic studies of the reaction strength for quasi-elastic reactions. Several of the experiments performed during the last year investigated the energy, neutron, and proton number dependence of the quasi-elastic cross sections. Besides inelastic excitation, neutron-transfer reactions are found to have the largest fields. For these strongest channels a systematic picture has emerged allowing a prediction of the reaction yields for these processes. In some cases the energy dependence of the reaction yield was measured over a large energy range. For the system $^{28}Si + {}^{208}Pb$ there exists now a complete data set for elastic and inelastic scattering and transfer reactions in the energy range from 152-420 MeV. Elastic and inelastic scattering in this system is well described by coupled-channels calculations over the full energy range. On the other hand, the analysis of the transfer data revealed that neutron transfer at forward angles, which is usually associated with large internuclear separations, shows some unexpected behavior. The fall-off of the cross section, if plotted as function of the distance of closest approach, was found to be independent of the bombarding energy for the one-neutron transfer reaction while it changes by a factor of two in the same energy range for the case of two-neutron transfer. This behavior cannot be understood within the framework of simple semiclassical models. Experiments in the system Ni + Sm covering the energy range from sub-barrier (using the Daresbury recoil mass separator) to higher energies (at ATLAS) are addressing a similar question. From the results obtained so far it appears that the simple semiclassical tunneling description is not adequate for these reactions. An extension of these quasi-elastic reaction studies to heavier masses (A>100), where almost no high-resolution data exist, is planned as soon as the second phase of the positive-ion injector is operational.

Besides inelastic scattering and neutron transfer, charged-particle exchange reactions are important reaction modes since they allow for the dissipation of energy in the collision process. From a study of one- and two-proton transfer reactions induced by medium-weight nuclei, it appears that the probability of two-proton transfer is enhanced with respect to one-proton transfer. Such behavior is predicted by calculations describing the pair transfer as a tunneling process between two superconducting nuclei ("Nuclear Josephson effect"). This question was addressed in a recent experiment by studying proton transfer reactions in the (closed neutron shell) nuclei ^{36}S + ^{92}Mo with good mass and charge resolution. Similar experiments with ^{86}Kr are planned for the future.

More complicated deep-inelastic multi-particle transfer reactions can be used to produce nuclei away from the valley of stability. This reaction mode was used to produce the extremely neutron-rich isotopes ^{67}Fe, ^{68}Co and ^{72}Ni in the systems ^{76}Ge + ^{186}W,^{138}Ba. Deep-inelastic processes are also found to produce nuclei with very large deformations, especially at energies in the vicinity of the Coulomb barrier. In order to investigate these deformed nuclei in more detail the γ decay of these reaction products was measured for the system Ni + Sn using particle-γ coincidence techniques with the Argonne-Notre Dame BGO ball.

Other experiments studied the neutron-number dependence of the nucleon transfer processes in the systems $^{76,82}Se$ + $^{192,198}Pt$, $^{58,64}Ni$ + $^{92,100}Mo$ and the feasibility of particle-γ coincidence measurements to locate high-j states in actinide nuclei. The excitation energies for these high-j-states are important input parameters for calculating the stability of superheavy nuclei. The Compton-suppressed Ge detectors from the Argonne-Notre Dame BGO spectrometer have also been used successfully to study the population of high-spin states in quasi-elastic transfer reactions.

The experiment studying the charge-state dependence of the internal conversion decay in ^{57}Fe has been completely analyzed; detailed comparisons of the experimental results with Monte Carlo simulations and relativistic Hartree-Fock calculations have been started. An extension of these measurements to heavier nuclei is planned as soon as the second phase of the positive-ion injector is operational.

a. Measurement of Reactions at Sub-Barrier Energies Using a Recoil Mass Separator (R. R. Betts, T. Happ, K. E. Rehm, A. Wuosmaa, C. N. Pass,* A. E. Smith,* J. S. Lilley,† and A. N. James,‡)

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 singles 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 have recently been published.

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. 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 data have been submitted for publication.

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To further investigate some of the ideas relating to the slope anomaly we have carried out some experiments at ATLAS using the split-pole spectrograph. The aim of these experiments is to measure spectra and angular distributions of one- and two-neutron transfer on $^{154,144}Sm$. This will enable us to extract angular distributions, and hence the dependence of the transfer probability on distance of closest approach, as a function of final nucleus excitation energy and thus test the hypothesis that the slope anomaly is associated with "cold" final-state population as advanced above. The first attempts at these measurements have shown that the experiments are indeed feasible.

b. Elastic and Quasielastic Scattering for $^{76,82}Se + ^{192,198}Pt$
(F. L. H. Wolfs, K. E. Rehm, W. C. Ma,* J. P. Schiffer, and T.-F. Wang†)

Our systematic study of the neutron-number dependence of the quasielastic scattering cross sections in the Ni + Sn system showed that the quasielastic strength increases for the ^{58}Ni-induced reactions while it is constant for the ^{64}Ni-induced reactions. This behavior has not yet been understood. Both Ni and Sn have a closed proton shell (Z=28 and Z=50) and the possible influence of shell effects on the total quasielastic cross section can therefore not be ruled out. In order to study the dependence of the quasielastic cross sections on neutron number for a system where shell effects should be minimal, we have measured elastic and quasielastic transfer yields for $^{72,82}Se + ^{192,198}Pt$ at 25% above the Coulomb barrier.

The measured one-neutron pickup and stripping yields are in good agreement with the observed systematics in other heavy-ion interactions. However, the total quasielastic yields for Se + Pt show a behavior similar to that observed for the Ni + Sn system; the total quasielastic yields for the ^{76}Se-induced reactions increase with increasing target mass, while the strength for the ^{82}Se-induced reactions is constant. The results of these measurements will be submitted for publication in 1990.

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c. One- and Two-Particle Transfer Reactions in $^{36}S + ^{92}Mo$
(A. H. Wuosmaa, B. G. Glagola, T. Happ, W. Kutschera, M. Nilsson, K. E. Rehm, and F. L. H. Wolfs)

It is well established that in heavy-ion reactions involving nuclei with closed-proton and open-neutron shells the two-neutron transfer probabilities can be strongly enhanced over what might be expected from a simple two-step transfer mechanism. We wished to investigate whether the same is true for proton transfer in a system involving nuclei with closed-neutron shells. In order to examine this problem, we have studied one- and two-particle transfer reactions in the system $^{36}S + ^{92}Mo$.

We bombarded targets consisting of 100-μg/cm^2 ^{92}Mo evaporated on 40-μg/cm^2 ^{12}C backings with a 4-pna ^{36}S beam from the ATLAS accelerator. The reaction products were detected using an Enge split-pole spectrometer. The focal-plane detection system consisted of a parallel-plate avalanche counter coupled with a Bragg-curve detector. With this assembly we obtained single-unit mass and charge resolution for the reaction products arising from one- and two-neutron, and one- and two-proton transfer. We measured angular distribution data for these reactions in steps of $\Delta\theta_{lab}$=2.5° around the grazing angle at two beam energies, 141 and 182 MeV.

Assuming pure Coulomb trajectories, the angular distribution data can be transformed into a measure of transfer probability versus distance of closest approach. Deviations of the shapes of the transfer-probability curves from the expectations derived from simple semi-classical models of the reaction can provide evidence for subtler quantum-mechanical effects in these systems. We are particularly interested in comparing the two-proton transfer strength to that of the one- and two-neutron transfer. An enhancement of the two-proton transfer probability could provide information about proton pairing correlations near the middle of a proton shell. The analysis of these data is presently underway.

d. Neutron Transfer Reactions in the Ni + Mo System
(F. L. H. Wolfs, K. E. Rehm, B. Glagola, W. Kutschera, S. Sanders, T.-F. Wang,* 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. Fusion cross sections measured recently 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 data from these measurements have been analyzed. The one-neutron stripping (^{A}Ni -> ^{A-1}Ni) yields are in agreement with the systematics observed in other heavy-ion reactions, and decrease with more negative Q-value. In contrast, the one-neutron pickup (^{A}Ni -> ^{A+1}Ni) yields are lower than expected for reactions involving ^{100}Mo, and higher than expected for reactions involving ^{92}Mo. The pickup cross sections are independent of Q-value. The total reaction cross section obtained from the measured elastic scattering angular distribution for ^{100}Mo + ^{64}Ni is accounted for by the sum of the fusion and quasi-elastic scattering yields. The results of these measurements will be submitted for publication in 1990.

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e. Systematic Behavior of One- and Two-Nucleon Transfer Reactions Induced by Medium-Weight Projectiles (K. E. Rehm, D. G. Kovar, C. Beck,* A. Van den Berg,† L. L. Lee,‡ W. C. Ma,§ F. Videbaek, and T.-F. Wang¶)

For one-nucleon transfer reactions the distorted-wave Born approximation (DWBA) theory is very successful in predicting absolute cross sections. For reactions induced by medium-weight ions these calculations become very time consuming because of the increasing number of single-particle states which have to be taken into account. Two-nucleon transfer reactions, on the other hand, cannot be described successfully within simple one-step (DWBA) calculations. A knowledge of these transfer cross sections is important since it has been found that they can strongly influence various reaction channels such as fusion and elastic and inelastic scattering. Since in these cases a knowledge of energy- and angle-integrated cross sections is sufficient, a simpler method for predicting the yields for one- and two-nucleon reactions has been developed.

We have studied a variety of heavy-ion-induced transfer reactions with projectiles in the mass range between A=28-82 on a large number of target nuclei using the split-pole spectrograph and its focal-plane detector which allowed complete element and isotope separation of the outgoing particles. For the strength of the angle- and energy-integrated one- and two-neutron transfer cross sections a systematic picture emerged. The strength of the cross sections depends strongly on the ground-state Q-value and on the binding energy of the transferred particle. The Q-value and binding energy dependence can be understood within a simple model which is based on the optimum Q-value picture for heavy-ion-induced transfer reactions. The systematics for one-neutron transfer reactions have been published. We have extended this analysis to two-neutron and charged-particle transfer reactions. For the two-neutron case it is interesting to note that the same Q-value dependence is observed with a strength which, for the same Q-value, is about 1/4 of the strength for the corresponding one-neutron transfer reaction.

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A similar description also works for charged-particle transfer reactions, although at the moment the data base for these cases is smaller. The interesting observation for charged-particle transfer is that the ratio for the cross sections between one- and two-particle transfer reactions which was about 1/4 for the neutron case increases to 1/2 for the proton case, indicating a possible enhancement of the two-proton transfer with respect to the one-proton transfer.

These results have been submitted for publication. We plan to investigate this possible enhancement in more detail using nuclei involving closed-neutron shells.

f. Energy Dependence of the One- and Two-Neutron Transfer Reactions
(K. E. Rehm, F. L. H. Wolfs, D. G. Kovar, J. J. Kolata,* and R. Vojtech†)

Nucleon transfer at large internuclear distances is usually thought to be governed by the tail of the wave function associated with the transferred nucleon. As a result the falloff of the cross section for one-neutron transfer, if plotted vs. the distance of closest approach, is proportional to the square root of the binding energy of the transferred neutron. For two-neutron transfer reactions one expects a slope which is about twice as steep as the slope of the corresponding one-neutron reaction. It has been found in a variety of cases that there are many exceptions to this simple scaling law. The slope of the two-neutron transfer reactions is usually similar to the slope of the one-neutron transfer.

We have studied the energy dependence of the falloff in the system $^{28}Si + ^{208}Pb$. Inelastic scattering and transfer reactions have been studied previously at E_{lab} = 152, 166 and 215 MeV at the split-pole spectrograph. For the transfer probability (transfer cross section divided by the Rutherford cross section) as function of closest approach (assuming Coulomb trajectories) of the one-neutron transfer reaction one observes that the falloff is in good agreement with the theoretical expectation at all three energies. For two-neutron transfer one finds agreement only at the lowest bombarding energy (152 MeV) whereas the falloff becomes less steep at higher energies. Similar

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†SUNY, Stony Brook, NYobservations have been made for the system ^{58}Ni +

^{208}Pb. Two possible explanations for this behavior are being investigated. One involves contributions from two trajectories passing the nucleus at different distances but emerging at the same scattering angle. Another one questions the applicability of classical trajectories for these systems and the possible dominance of diffraction processes for reactions with a very localized form factor.

g. Study of Neutron-Rich Nuclei Produced in the ^{76}Ge + ^{186}W,^{138}Ba Systems (K. E. Rehm, C. N. Davids, R. V. F. Janssens, F. L. H. Wolfs, G. E. Rathke,* and H.-J. Körner*)

Neutron-rich nuclei in the Fe-Ge region are important for a better understanding of the r-process in nucleo-synthesis. Experimentally these nuclei are, however, difficult to produce, since they have very small production cross sections in the fission process. We have investigated to what extent deep-inelastic reactions can be used in order to produce these nuclei with reasonable yields. The experiments were performed in the split-pole spectrograph with the parallel-plate avalanche Bragg-curve detector in its focal plane. This system allowed a complete determination of mass, nuclear charge, atomic charge state and reaction Q-value. We have used a ^{76}Ge beam on ^{138}Ba and ^{186}W targets at energies of 430, 520 and 680 MeV, in order to find the optimum conditions for producing these neutron-rich isotopes. The analysis of these data is still in progress. The following results have been obtained so far:

i) The main flow of mass and charge transfer produces elements with $Z < Z_{projectile}$. This behavior can be understood from the structure of the underlying mass valley in this region.

ii) At energies close to the Coulomb barrier, mainly neutron transfer is observed. The production cross section for neutron-rich isotopes in the Fe-Ge region is very small.

iii) The heaviest isotopes in the Fe-Ni region which have been observed are ^{67}Fe, ^{68}Co and ^{72}Ni.

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At the moment we are investigating the extent to which the energy dependence of the production cross sections can be understood within a random-walk model which treats the nucleon transfer reactions as successive one-step nucleon transfer reactions.

h. Deep-Inelastic Scattering in Heavy-Ion Reactions at Energies around the Coulomb Barrier (F. L. H. Wolfs, P. Benet,* M. P. Carpenter, D. H. Henderson, R. V. F. Janssens, T. L. Khoo, E. F. Moore, K. E. Rehm, A. Wuosmaa, K. Beard,† and S. J. Sanders‡)

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 those of fusion. The total kinetic energy of the deep-inelastic reaction products indicates that they are emitted from a strongly-deformed system.

We have studied the γ-ray decay of the deep-inelastic scattering products in a particle-γ coincidence experiment carried out using the Argonne-Notre Dame BGO γ-ray facility. In this measurement, a 294.9-MeV ^{58}Ni beam was incident on a 50-μg/cm^2 ^{124}Sn target. Deep-inelastic scattering fragments were detected in kinematic coincidence in two large-area Parallel-Gridded Avalanche Counters (PGACs). The detectors were positioned at angles of ±35° with respect to the beam direction, and each detector covered an angular range of ±15°. In this configuration, only projectile- and target-like fragments with a reaction Q-value more negative than -20 MeV could be detected in kinematic coincidence. Only those events in which both deep-inelastic scattering products were detected in coincidence with at least one γ ray in either one of the germanium or the BGO detectors were recorded. A total of 40,000 events were recorded with at least one γ ray in one of the germanium detectors, while a total of one million events were recorded with γ rays only in the BGO detectors.

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The analysis of the data is currently in progress. The germanium energy spectra have been Doppler-shift corrected on an event-by-event basis, either assuming that the γ rays are emitted from the projectile-like or target-like fragment. These spectra show a rich line structure. Other aspects that will be studied are the γ-ray multiplicity (obtained from the BGO detectors) as a function of the reaction Q-value and center-of-mass scattering angle.

i. Study of High-j States in ^{233}Th (T. Happ, I. Ahmad, K. E. Rehm, M. P. Carpenter, E. F. Moore, B. G. Glagola, and F. L. H. Wolfs)

Studies in the rare-earth region show that high-j states are preferentially populated in the (^{16}O,^{15}O) reaction. We have used this reaction to investigate high-j particle states in ^{233}Th using a 200-μg/cm^2 ^{232}Th target. The ultimate goal of this program is to identify high-j states in ^{249}Cm, which has bearing on the stability of superheavy elements. Approximately 10 pnA of 150-MeV ^{16}O beam was incident on the ^{232}Th and the outgoing ^{15}O ions were analyzed with the Enge split-pole spectrometer and detected in a position-sensitive gas counter. The spectrometer angle was 44°, near the grazing angle. In the energy spectrum, we were able to identify the previously known 15/2 member of the 7/2-[743] ground-state band (Fig. I-1). We also identified two new peaks at 1.24 and 1.62 MeV, and because of the large cross section we assign the 1.24-MeV level to the 15/2 member of the 9/2-[734] band. The 252-keV level is found to be broader than the other two peaks suggesting that lower ℓ-value states are also populated. The cross sections for the three peaks are found to be 300, 100 and 50 μb/str, respectively.

Although large cross sections are signatures of large ℓ transfer, a more definite identification of these peaks can be made from the decay of these levels. For this purpose a particle-γ coincidence experiment was performed with the spectrograph aperture set at 5 msr. A special Faraday cup made of heavymet was used to minimize the background in the Ge detector. The device worked very well and allowed us to use 6-pnA current for the coincidence experiment. The coincidence experiment was run for only 20 h. This time was too short to observe any coincident peaks. However, the preliminary experiment shows that particle-γ coincidence experiments can provide information on de-exciting γ rays in longer runs.

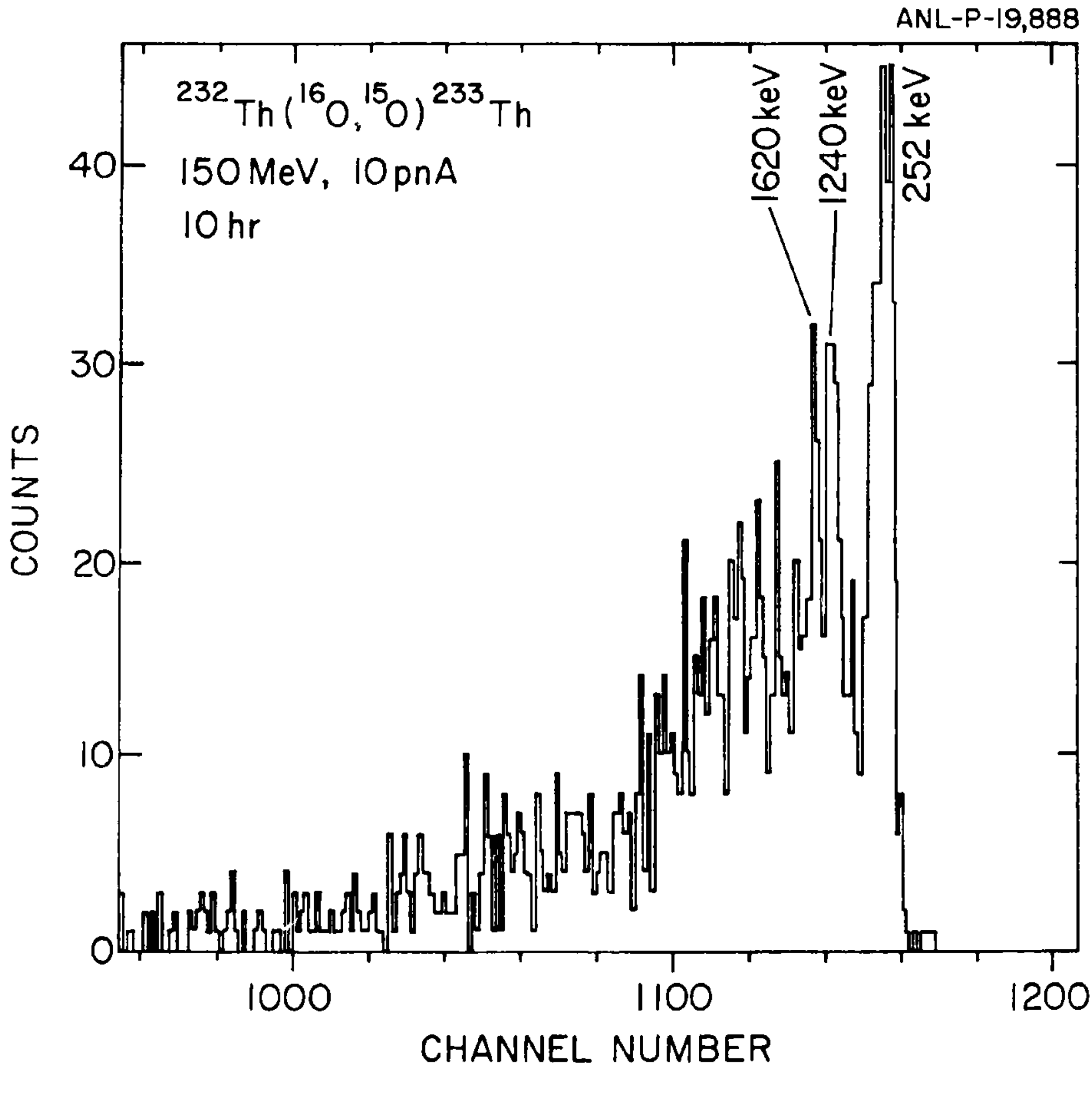

Fig. I-1. A spectrum of the outgoing ^{15}O ions produced in the $^{232}Th(^{16}O,^{15}O)^{233}Th$ reaction. The 252-keV peak represents the 15/2 member of the 7/2$^-$[743] rotational band.

j. Inelastic and Transfer Reactions in $^{92}Mo + ^{60}Ni$ Collisions Studied by γ-γ Coincidences (R. V. F. Janssens, T. L. Khoo, F. L. H. Wolfs, R. Broda,* M. A. Quader,* P. J. Daly,* R. Holzmann,† and W. C. Ma‡)

Transfer reactions induced by heavy ions with incident energies close to the Coulomb barrier have been intensively investigated using both charged-particle spectroscopy and particle-γ coincidence methods. The excellent energy resolution available in γ-ray spectroscopy allows the direct measurement of discrete state populations, and is particularly important when the target and/or projectile nuclei are deformed. The use of particle detection improves channel selectivity and yields valuable information about the reaction kinematics. A different approach is to forgo particle detection and to concentrate on acquiring more integrated information about transfer processes by means of γ-γ coincidence techniques. Here, the emission of known γ rays identify the final nuclei; an especially important feature is that the mutual excitation of both reaction products may be directly observed through coincidences between γ rays emitted from reaction partners. The advent of multi-detector arrays of Compton-suppressed Ge spectrometers has made this method particularly attractive because of the greatly improved detection sensitivity.

In a recent ^{92}Mo + 255-MeV ^{60}Ni experiment, which had as its principal objective the study of high-spin level structures in ^{149}Ho and ^{150}Er, the excellent γ-γ coincidence data acquired included many events arising from the quasi-elastic processes mentioned above. In addition to the strong inelastic channel, twelve transfer processes ranging from 1n to 2α transfer and involving excitation to high spin and moderately high energy were observed. For example, the yields of the inelastic scattering product nuclei are comparable to those of the fusion evaporation products. In the ^{92}Mo nucleus, states with excitation energies up to 6 MeV and spins $I \gtrsim 11$ were significantly populated, including rather strong population of known 8^+ and 11^- isomers. The latter states have complex multiparticle-hole configurations and it is clear that Coulomb excitation plays little part in their population, which probably occurs through a nuclear excitation process. Similarly, the ^{60}Ni projectile is excited up to comparable energies and states up to the 7^- level at 5.35 MeV

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could be observed. For the transfer channels the following general conclusions can be derived:

(1) transfer reactions contribute a substantial fraction of the reaction cross section; (2) transfer of particles from the projectile to the target strongly dominates, but no clear correlation between the yields and the ground-state Q-values is apparent; (3) states up to high excitation energy and spin are observed, usually in both reaction partners; (4) in at least 2 cases there is firm evidence for neutron emission from one of the reaction partners following the transfer process; (5) states with complex particle-hole configurations are fed strongly in many cases. The analysis of the data continues. Comparisons with existing models will be performed.

k. Internal Conversion Decay Rates in Few-Electron Systems
(I. Ahmad, B. G. Glagola, W. Kutschera, K. E. Rehm, J. P. Schiffer, A. R. Barnett,* J. Copnell,* and W. R. Phillips*)

The internal conversion (IC) decay rates $\lambda_{Kq}, \lambda_{Lq}$, etc. for K- and L-conversion of a nuclear isomer in energetic few-electron ions of varying ionicities q, can be determined by observing the distribution of the ions in the focal plane of a magnetic spectrograph. Ions which change their charge because of IC during transit of the magnetic field are displaced in the focal plane by an amount which depends on the point in the spectrometer at which the IC occurs. This technique has been exploited to determine λ_{Kq} of the 14.4-keV state in ^{57}Fe for q=24 (He-like) and q=25 (H-like). These results, the first of their kind, have been published. In order to obtain information for lower charge states (q<24) computer simulations of the charge-changing trajectories of all ions in the magnet have to be made. Codes for these simulations have been developed, and the analysis of all the data is near completion. In addition to decay rates λ_{Kq}, the analysis will yield more accurate values for the K-shell fluorescent yields ω_{Kq}. The parameters λ_{Kq} and ω_{Kq} provide sensitive tests of atomic wave-function calculations for different numbers of orbiting electrons.

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The next experiment to study IC in highly-charged atoms is planned using the second phase of the positive-ion injector. This experiment will measure λ_{Kq} for the 9.3-keV state in the nucleus ^{83}Kr for q between 28 and 33. A method similar to that in the ^{57}Fe experiment will be used to produce a beam of ^{83}Kr in a distribution of charge states centered around q=30 and with a significant fraction of the nuclei in the 9.3-keV isomer. This experiment will be sensitive to differences in 2s electron wave functions with varying numbers of L electrons. These changes, and so the changes in λ_{Lq}, are relatively larger than the changes in λ_{Kq} for the 14.4-keV state in ^{57}Fe and the uncertainties in the decay rates determined for ^{83}Kr will thus be significantly smaller than for ^{57}Fe.

ℓ. Quasielastic Reactions of ^{28}Si on ^{208}Pb at Energies of 10 and 15 MeV/A (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†)

The analysis of the data obtained for quasielastic scattering of ^{28}Si on ^{208}Pb at 280 MeV and 420 MeV is progressing at the University of Notre Dame. The analysis for elastic and inelastic scattering was completed including coupled-channels calculations performed with the code PTOLEMY. At present the angular distributions for few-nucleon transfer reactions are being analyzed. Together with previous results obtained at 152, 166 and 215 MeV these data will provide a good basis to study the energy dependence of quasielastic reactions.

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m. Quasielastic Scattering of ^{30}Si on ^{208}Pb

(K. E. Rehm, D. G. Kovar, G. S. F. Stephans,* M. F. Vineyard,†
J. J. Kolata,‡ R. J. Vojtech,§ and L. A. Lewandowski‡)

The analysis of quasi-elastic scattering of ^{30}Si on ^{208}Pb has been completed and a paper with the results has been published.

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B. FUSION AND FISSION WITH HEAVY-ION BEAMS

The study of heavy-ion-induced fission and fission-like reactions constitute a substantial part of the research program at ATLAS. This part of the program encompasses studies of the fission decay of compound nuclei formed under unusual conditions such as sub-barrier energies and very light systems, but increasingly the study of non-compound fission-like processes has become the major thrust of the program.

Present efforts are aimed at studying the reaction mechanism at sub-barrier energies in heavy-ion-induced fusion via the fission decay of the fused systems. It has recently been reported that the fission angular anisotropies in ^{12}C- and ^{16}O-induced reactions on actinide nuclei are substantially larger than expected, a discrepancy which has been interpreted as caused by unaccountably large spins of the fused systems. We have repeated some of these measurements but separated fragments from compound fission and sequential fission decay of excited target-like nuclei by measuring the time of flight of the fragments in contrast to earlier measurements, which included the latter component. It appears that the exclusion of the sequential fission events reduces the angular anisotropy somewhat, but it does not remove the discrepancy altogether.

When projectiles heavier than about mass A=24 are used, the probability for complete fusion of the projectile and target becomes progressively hindered. This results in the emergence of fission-like processes, which have some of the characteristics of direct reactions. Several studies are focussing on characterizing this process, also labelled quasi-fission. We have measured the entrance-channel dependence of this process by forming ^{214}Th via the $^{32}S+^{182}W$, $^{48}Ti+^{166}Er$, and $^{60}Ni+^{154}Sm$ reactions.

The excitation of angular-momentum-bearing modes of the di-nuclear system, which are excited in both compound fission and fission-like reactions, is the subject of intense study. Traditionally, one of these modes, the tilting mode, has been studied by measuring the angular distribution of fission fragments. In quasi-fission reactions it is necessary to measure at small angles in order to derive information on the excitation of the tilting mode. We have performed such studies by using the Enge split-pole spectrograph to complement measurements with Si-detectors at larger angles for the $^{58}Ni+^{208}Pb$ reaction. In the future such studies will be carried out at the Fragment Mass Analyzer, an instrument ideally suited for this type of experiment.

The other di-nuclear modes which are excited in fission reactions, the so called twisting, bending, and wriggling modes, have also been studied in an inclusive manner by measuring the total γ-ray multiplicity from the fragments. When interpreting these data within the context of simple statistical models, we are unable to explain several of the pertinent features seen experimentally. Future studies of this type are aimed at measuring the intensities and angular distribution of discrete γ lines in coincidence with the fission fragments in order to try to isolate some of these modes.

In a series of studies in the mass region A = 60-80 it has been found that a small, but measurable, fraction of the total reaction cross section has all the expected features of fission. Detailed mass, energy, and angular distributions have been measured for the $^{32}S+^{24}Mg$ system, which all point to fission of the ^{56}Ni as being responsible for the observed products. In addition we have measured coincident γ rays in order to study the distribution of spin and excitation energy between the two fragments.

a. Sub-Barrier Fission in the $^{16}O + ^{232}Th$ Reaction
(B. B. Back, H. Ikezoe,* B. G. Glagola, D. Henderson, and T. Happ)

In recent experiments by R. Vandenbosch (Seattle) and H. Zhang (Beijing) it has been found that sub-barrier fission of $^{16}O+^{232}Th$ leads to angular anisotropies, which are substantially larger than expected. The data from these experiments include the contribution from sequential fission decay of Th-like nuclei, which are excited to energies above the fission threshold by inelastic and transfer reactions. Since the size and effect of this contribution to the data is not very well known we have performed an experiment at ATLAS to try to isolate the sequential fission contribution by time-of-flight measurements of the fragment masses, which are slightly smaller than for fragments from the fusion-fission process. Although the final analysis of the data is not yet complete, it appears that it is possible to isolate this contribution to the data, and thus settle this open question concerning the large anisotropies at sub-barrier energies. If the effect remains even after removing this contribution, we plan to carry out further experiments to search for the origin of these large sub-barrier anisotropies.

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b. <u>^{3}He-Induced Fission Angular Distributions</u> (B. B. Back, I. Ahmad, P. Benet, J. Done, P. Fernandez, T. Happ, and D. Henderson)

The main reason that so much importance is attached to the abnormally large fission anisotropies observed in the $^{16}O+^{232}Th$ reaction, is that the fission decay of the ^{248}Cf compound nucleus formed in this reaction is believed to be well understood from studies of the $\alpha+^{244}Cm$ reaction, which leads to the same compound system. In order to verify these old results, we have measured the angular distribution from a similar reaction, namely $^{3}He+^{245}Cm$. Both of these light-ion reactions are carried out at above-barrier energies, which substantially reduces the uncertainties of the analysis associated with the spin distribution of the fissioning system. The $^{3}He+^{245}Cm$ experiment was carried out at three beam energies, namely 22.3, 24.3, and 27.1 MeV, using beams from the positive-ion injector generated in the ECR source. In fact, this was the first complete experiment utilyzing beams from the new injector.

The target material was obtained from the Heavy Element Group of the Chemistry Division at Argonne, and was deposited onto a thin Ni backing by a molecular plating technique. A target thickness of approximately 100 $\mu g/cm^2$ over a circular spot of 3-mm diameter was achieved.

The fission anisotropies observed in the experiment are essentially in agreement with the earlier results for the $\alpha+^{244}Cm$ reaction. Therefore, it does not appear that the large fission anisotropies observed in the $^{16}O+^{232}Th$ system can be attributed to an incomplete understanding of the fission decay from the ^{248}Cf system. Rather it seems to reflect some, as yet poorly understood, feature of the $^{16}O+^{232}Th$ reaction mechanism. The combined results for the $^{16}O+^{232}Th$ and $^{3}He+^{245}Cm$ reactions will be submitted for publication.

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

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 were determined from the time of flight between the target and detectors, utilizing the excellent time structure of the beam. The data obtained in this experiment are presently being analyzed.

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d. Energy Dissipation, Mass Flow and Excitation of the Tilting Mode in the ^{58}Ni + ^{208}Pb Reaction (B. B. Back, J. G. Keller, B. G. Glagola, S. J. Sanders, F. Videbaek, B. D. Wilkins, D. Henderson, 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 $\theta = 10^{\circ} - 120^{\circ}$ in an array of 12 single Si-detectors. The masses of reaction products were determined from the measured energy and the time of flight between the target and 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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e. Excitation of the Tilting Mode in Heavy-Ion-Induced Reactions
(B. B. Back, B. G. Glagola, K. E. Rehm, and S. J. Sanders*)

We have measured the angular distributions of reaction products (deep-inelastic, quasi-fission, and compound fission) at angles near the beam axis for specific masses in order to study the tilting mode in nuclear reactions initiated by heavy ions. The first experiment in a series has been carried out in the Enge split-pole spectrograph using the reaction $^{58}Ni+^{208}Pb$ at energies of 410, and 500 MeV. The data are presently being analyzed. When the Fragment Mass Analyzer becomes operational, we intend to continue the experiments on this instrument, where precise measurements of the angular distribution for specific masses can be carried out, even at the most forward angles.

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f. 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

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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 and generate folding-angle spectra. The time and mass calibrations are nearly complete. Final analysis of the data is continuing.

g. 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 $^{28}Si + ^{50}Cr$ (measured at Daresbury) which populates the adjacent compound nucleus ^{78}Sr in the same region of excitation energy and angular momentum; the 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

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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 Ph.D. thesis of P. M. Evans and has been published this year.

h. 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,ǂ F. L. H. Wolfs, K. Beard,§ and D. Habs¶)

The initial experiment has been analyzed and the results have been submitted for publication. Recently, a second experiment has been carried out in a larger scattering chamber, which was connected to the Argonne-Notre Dame gamma-ray facility. Coincident fragments were registered in two large-area position-sensitive avalanche detectors centered at 35° and -35°, respectively. Gamma rays from the fragments were measured in the BGO-detector array and eight of the Compton-suppressed Ge detectors. The data from this experiment are presently being analyzed.

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i. 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 in 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 ^{58}Ni, which allows for the reconstruction of the primary mass dependence prior to the second light-particle emission, was used. In our previous measurement of the ^{32}S+^{24}Mg system (reaching the ^{56}Ni compound nucleus system) we discovered the preferential decay to mass asymmetric fission channels with the greatest cross sections in channels where both reaction partners have a 4N, α-particle-like

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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 analysis of these data is presently being carried out.

j. Study of the $^{58}Ni+^{150}Nd$ and the $^{58}Ni+Pt$ Reactions Near the Coulomb Barrier (B. B. Back, T. Happ, W. Kutschera, J. P. Schiffer, S. Gelberg,* A. Marinov,* H. Folger,† D. Kolb,‡ and W. Oelert§)

An experiment to study the $^{58}Ni+^{150}Nd$ and the $^{58}Ni+Pt$ reactions has been started using a ^{58}Ni beam from ATLAS. The goal of the experiment was to search for long-lived fission activities from the $^{58}Ni+Pt$ reaction. For this experiment, a moving-foil apparatus built in Jerusalem was installed behind the scattering chamber in target area III. In this system the position of four catcher foils is synchronized with the beam sweeper at the entrance of ATLAS. With the beam on, all four catcher foils are positioned behind the target and a degrader foil in order to catch the reaction products. When the beam is off, each foil is moved to a new position in between two Si surface barrier detectors, where singles and coincidence spectra of fission fragments and α particles can be measured and lifetimes of the various groups be determined. The results of various runs with different degrader and catcher foils identified evaporation residues for the bombardment of ^{150}Nd with 305-MeV ^{58}Ni. Total cross sections of about 10 μb were found for evaporation residues in the vicinity of the compound nucleus, identified by their α decay. In the bombardment of Pt with ^{58}Ni of 305 and 334 MeV energy, a search for a long-lived fission activity gave negative results with an upper limit for the cross section of about 7 nb. On the other hand, at the higher bombarding energy surprisingly large α activities were found, with cross sections exceeding 130 μb. The energies of the α particles correspond to neutron-deficient nuclei in the Po-At-Rn region which can be produced via deep inelastic or quasi-fission processes. The cross section, however, seems to be quite large for this region of nuclei where the fission probability is substantial.

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

The data from this experiment have been analyzed and a manuscript is presently being prepared for publication.

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ℓ. <u>Relaxation of Angular Momentum in U-induced Quasifission Reactions</u> (B. B. Back, S. Bjørnholm,* T. Døssing,* A. Gobbi,† K. Hildenbrand,† W. Q. Shen,‡ and S. P. Sørensen§)

A manuscript describing this work has been completed and submitted for publication.

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§University of Tennessee, Knoxville, TN

C. GAMMA-RAY SPECTROSCOPY STUDIES

This research program focuses on three major areas: (a) studies of nuclear structure at very high spin, on and above the yrast line, with particular emphasis on the properties of superdeformed states, (b) investigations of the properties of the compound nucleus decay and (c) research on reflection asymmetric nuclear shapes.

A major focus of the Argonne work has been on the study of superdeformation. In the past year, work at this laboratory has provided first evidence for a new region of the periodic table where superdeformation occurs: the A~190 region. First evidence was found in ^{191}Hg and considerable effort has subsequently been focussed on exploring these superdeformed structures in neighboring nuclei.

All projects described in this section have taken advantage of the capabilities of the Argonne-Notre Dame BGO γ-ray facility which consists of 50 hexagonal BGO detectors (used mainly as a sum-energy/multiplicity filter) surrounded by 12 Compton-suppressed Ge detectors. A wide variety of computer programs have been developed by the collaboration which provide assistance with setting up the experiments (gain matching, adjustment of the constant fraction discriminators, etc.) and with the data reduction. Furthermore, a scattering chamber for coincidence measurements between γ rays and particles identified either by ΔE-E or time-of-flight techniques is also available. Dedicated target chambers have been constructed for other experiments (g-factor measurements, lifetime measurements, etc.). A support for up to 7 Compton-suppressed spectrometers also exists at the magnetic spectrograph for particle-γ coincidence experiments with this instrument. The first design studies of a support for the use of the spectrometers in conjunction with the Fragment Mass Analyzer have taken place.

Several projects are joint efforts with outside user groups from Notre Dame, Purdue, INEL-Idaho, Louvain, Manchester, Rochester, Rutgers and Tennessee.

C.a. Superdeformed Nuclei: A New Region Around A~190

In recent years, research on nuclear structure at very high spin has been concentrated mainly on superdeformation at most laboratories. After the discovery at Daresbury of a band of 19 transitions corresponding to the rotation of the superdeformed ^{152}Dy nucleus (axis ratio ~ 2:1), several other nuclei in the same mass region have been shown to display the same phenomenon. Among the latter is the ^{151}Dy nucleus where a superdeformed band was found in experiments performed at ATLAS. Following these discoveries some of the important questions to be answered concern (i) the existence of other regions of the nuclear chart where superdeformation may occur and (ii) the population mechanism responsible for the unexpectedly high yield observed in the superdeformed bands. Calculations by R. R. Chasman, described elsewhere in this document, suggested that the A=190 region is particularly interesting in that there are large Coulomb effects 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 well depths 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 was 1.65: 1 (β=0.55).

A series of experiments at ATLAS proved conclusively that a new region of superdeformation exists around A~190. In ^{191}Hg, a band of 12 transitions with energy spacings consistent with the very large moment of inertia expected for a superdeformed shape was found. The quadrupole transition moments were measured and the derived quadrupole deformation ($\beta\simeq$0.55) corresponds to the expected very large prolate shape (axis ratio 1.65:1). The band was found to persist to much lower rotational frequency than in the A~150 region and the possibility that superdeformation persists to very low spins in this region must be contemplated. Evidence was also found for superdeformation in the neighboring even-even isotopes ^{190,192}Hg: in all cases the deformation was measured to be very large and the dynamic moments of inertia were shown to increase with rotational frequency. In ^{191}Hg, a detailed analysis also revealed two excited superdeformed bands. Thus, it appears that detailed spectroscopy in the second well is feasible because of the excellent detection sensitivity achieved with the Argonne-Notre Dame BGO γ-ray facility. The results have been interpreted in cranked Strutinsky calculations which highlight the role of specific high-j orbitals at large deformation. Comparisons between the data and the calculations also provide information on changes in pairing at large deformations. Experiments to study in detail the deexcitation out of the superdeformed band towards the yrast line have started; they focus on possible time delays involved in the link between the two classes of states. The A~190 region proves to be a fertile ground for a variety of nuclear shapes; a band structure has been found in ^{191}Hg which corresponds to the so-called "non-collective" prolate shape ($\beta \simeq 0.2$, $\gamma = -120°$). Experiments aimed at the understanding of the feeding mechanism of the superdeformed bands in this mass region were also performed and the results can be compared with the results of a similar experiment performed last year for ^{152}Dy. It was shown that in all cases the entry points into the nucleus for states in the superdeformed bands are located at higher spin and at an excitation energy closer to the yrast line than for the other yrast or near-yrast states.

a.1. First Observation of Superdeformation in the A=190 Region

(E. F. Moore, R. V. F. Janssens, I. Ahmad, R. R. Chasman, T. L. Khoo, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* P. Benet,† Z. W. Grabowski,† M. W. Drigert,‡ and J. A. Cizewski§)

Superdeformation was first proposed some twenty years ago to explain the fission isomers observed in the actinides. The interest in the mechanisms responsible for this exotic shape (i.e. mainly shell effects) has increased enormously with the discovery of a discrete-line superdeformed band in ^{152}Dy. 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. A study of the ^{191}Hg nucleus represented our first attempt to identify the presence of superdeformation in a new region. In this nucleus, a band of 12 transitions with properties consistent with a very large prolate shape was found.

Two sets of data were used: one was obtained with thin ^{160}Gd targets, consisting of two isotopically enriched 500-μg/cm^2 self-supporting foils stacked together, while the other one used a 1-mg/cm^2 ^{160}Gd target on which 14-mg/cm^2 Au was evaporated in order to stop the recoiling evaporation residues. In all measurements the (^{36}S,5n) reaction was used at a beam energy of 172 MeV. The experiments were performed at the ATLAS accelerator with the Argonne-Notre Dame BGO γ-ray facility which consists of 50 hexagonal BGO elements surrounded by 12 Compton-suppressed Ge spectrometers.

In the analysis, γ-γ coincidence matrices were obtained where high multiplicity events were selected by requiring that at least 10 detectors of the array fired in prompt coincidence with the Ge detectors. The final matrices contained 95×10^6 events for the thin-target run; the corresponding number for the thick-target measurement is 69×10^6. In both cases the multiplicity condition given above ensures that at least 60% of the events correspond to the reaction channel of interest.

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As stated above, the analysis of the data from the measurements with the thin targets first revealed the presence of a band of 12 coincident transitions extending from 350 to 754 keV with an average energy difference of 37 keV, i.e. consistent with the spacing expected for a superdeformed shape (the corresponding dynamic moment of inertia $J^{(2)}$ is ~ 110 $\hbar^2$ MeV^{-1}). This is the first evidence for superdeformation in nuclei so close to the doubly-magic nucleus ^{208}Pb. The E2 multipolarity of all the γ rays was inferred from directional correlation ratios. One of the transitions in the band has the same energy (390.5 keV) as the $17/2^+$-$13/2^+$ transition in ^{191}Hg. The intensity of this transition is always larger than that of any other transition in the band by about 25% and it is proposed that the excess intensity comes from the decay of the band, at least partly, through the $17/2^+$ state. This supports the assignment of the newly observed band in ^{191}Hg. Even though the value of $J^{(2)}$ is consistent with a superdeformed shape, a more direct determination of the deformation is desirable since particle alignment coupled with a strong interaction can result in large apparent values of the moment of inertia. A measurement of lifetimes was performed using the Doppler-shift attenuation method with the thick target. The data are consistent with Q_0=18$\pm$3 e.b. where the errors include uncertainties in the slowing down process and in the sidefeeding intensities. The measured value of Q_0 implies a deformation β=0.55, in agreement with the deformation calculated by Chasman and we conclude that a superdeformed band has been observed in ^{191}Hg. This result has been reported in a publication. It has also stimulated further experimental work in this new region of superdeformation; this is reported below.

a.2. <u>Excited Superdeformed Bands in ^{191}Hg</u> (M. P. Carpenter, R. V. F. Janssens, E. F. Moore, I. Ahmad, P. B. Fernandez, T. L. Khoo, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* M. W. Drigert,† P. Benet,‡ R. Wyss,§ W. Satula,§ W. Nazarewicz,¶ and M. A. Riley¶)

Following the discovery in ^{191}Hg of a band of 12 transitions corresponding to the rotation of a nucleus with a superdeformed prolate shape, further investigations of this nucleus were initiated in order to see if detailed spectroscopy studies in the superdeformed minimum are possible. This investigation was motivated in part by the results of cranking calculations which predicted the presence of several excited bands built on specific excitations into high-j orbitals which play an important role at large deformations.

The results were derived from the same sets of data used to identify the first superdeformed band in ^{191}Hg. The detailed analysis of the coincidence matrices revealed the presence of two bands with an average energy difference of 36 and 37 keV, respectively. These values are very similar to that measured for the first superdeformed band (band 1) in this same nucleus. The two bands are rather weak and most of the transitions are contaminated by other lines of stronger intensity. Nevertheless, the coincidence relationships between the various transitions in the two bands were verified from the individual gates as well as from the observation of the expected regular grid pattern in the two-dimensional γ-γ matrix. From the data taken with a thick target, lifetime information was derived for a few transitions. Even though the error bars are rather large, it is clear that the lifetimes of the new states are of the same order as the lifetimes of the superdeformed states of band 1 and we conclude that two new superdeformed bands have been observed in ^{191}Hg.

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In order to interpret these results, we have performed further cranked shell-model calculations with pairing using a Woods-Saxon potential. These calculations indicate that the yrast superdeformed configuration is built on the aligned $\nu 7_{3/2}$ routhian (from the third N=7 $j_{15/2}$ neutron orbital) and we associate this configuration with band 1. Bands 2 and 3 can be understood as the signature partners built on the [642]3/2 orbital (from the $i_{11/2}$ orbital). The evolution of the calculated $J^{(2)}$ values for the 3 bands as a function of rotational frequency was also investigated. The major contribution to the rise of $J^{(2)}$ in the three bands is caused by the gradual alignment of the $\pi 6^4$ protons (from the $N = 6$ $i_{13/2}$ proton orbital). The neutron contributions differ for band 1 and bands 2 and 3: the neutron contribution to $J^{(2)}$ remains almost constant for band 1 while an additional increase is calculated for bands 2 and 3. The calculations reproduce the data rather well.

A manuscript reporting these data has recently been submitted for publication. These exciting new results clearly indicate that detailed spectroscopy in the second well is possible. Further measurements aiming (i) at testing the power of the cranking calculations in other nuclei of this mass region and (ii) at identifying other collective excitations in the superdeformed minimum are planned.

a.3. Nucleon Alignment in ^{191}Hg: A Competing Mechanism at Moderate Spins
(R. V. F. Janssens, M. P. Carpenter, E. F. Moore, I. Ahmad, T. L. Khoo, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* M. W. Drigert,† Z. W. Grabowski,† P. Benet,‡ T. Bengtsson,§ and I. Ragnarsson§)

During the search for superdeformation in ^{191}Hg outlined above, a wealth of data was obtained for other states in this nucleus. In this way, new information was also derived on the behavior of this nucleus at lower spin. Here, we focus on a new band-structure with properties suggestive of so-called "non-collective" generation of angular momentum, i.e. a structure corresponding to a non-collective prolate shape (γ=-120°). Our most recent findings combined with the results of earlier studies available from the literature make the ^{191}Hg nucleus a good example for a rich variety of phenomena indicative of different nuclear shapes (oblate-collective, superdeformed and prolate non-collective), and analogies can be drawn with the level structure of ^{152}Dy where particle alignment resulting in a non-collective oblate shape as well as rotation associated with small and very large (superdeformed) deformations have been reported.

The results presented here were derived from the data used in the superdeformation search outlined above. A total of 14 different band structures have been established in ^{191}Hg from this experiment (Fig. I-2), and the detailed level scheme is still under investigation. Of particular importance is the discovery of a new sequence of levels at excitation energies between 4587 and 8669 keV. The level ordering as well as the spin and parity assignments in the new sequence are rather firmly established because the γ

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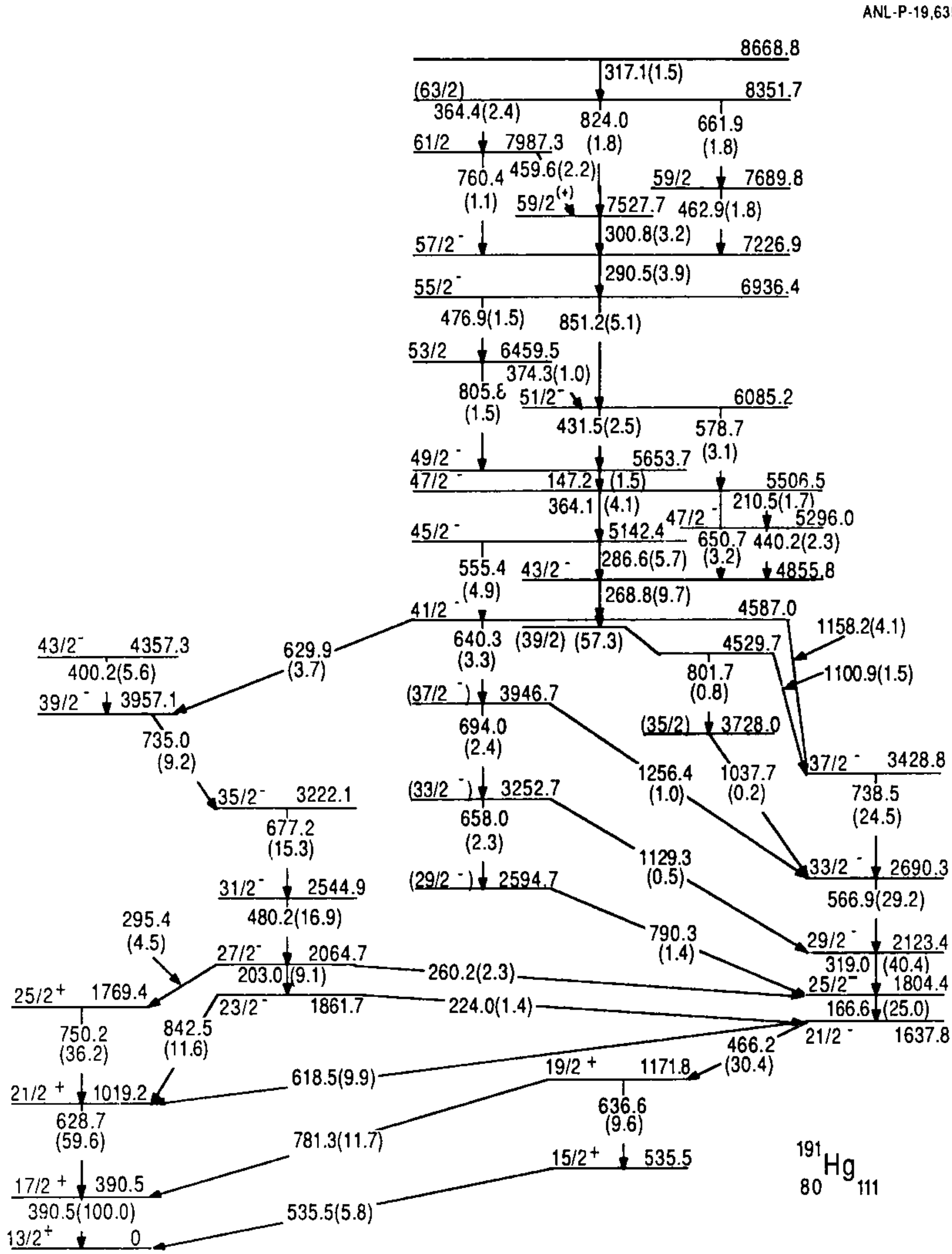

Fig. I-2. A partial level scheme of ^{191}Hg deduced from the present study. Excitation energies are relative to that of the 13/2+ level. Relative gamma intensities are given in parentheses.

decay usually proceeds through several pathways. Fifteen percent of all decays in ^{191}Hg proceeds through the $41/2^-$ level located at the bottom of this sequence. The measurements with the backed target indicated that all transitions in the new level sequence are emitted after the ^{191}Hg nuclei are fully stopped. This result implies that the lifetimes of the states or of the transitions feeding them are longer than a few picoseconds.

A noticeable feature of the level structure above the 41/2 level is that the transition energies vary greatly, and a large number of dipole and quadrupole transitions compete in the decay. This feature, together with the fact that the band decays towards several rotational structures, indicates that the new levels differ greatly in character from the rotational yrast states at lower excitation energy. These properties are very similar to those observed in nuclei with $A \simeq 150$. In these cases, the angular momentum is generated by the alignment of the spins of individual nucleons along a symmetry axis and the overall nuclear shape resulting from this "particle-alignment mode" is oblate. We propose that the new level structure in ^{191}Hg is also of single-particle character on the basis of this similarity, and we note that the lifetimes of the states discussed above are consistent with this interpretation.

We have carried out Nilsson-Strutinsky cranking calculations for ^{191}Hg. The following general features emerge: (1) for spins I=20-30 $\hbar$, two minima are present in the energy surfaces corresponding to collective near-oblate configurations ($\epsilon_2 \sim 0.15$, $\gamma \sim -40°$) and to aligned prolate non-collective configurations ($\epsilon_2 \sim 0.1$-0.15, $\gamma \sim -120°$), respectively; (2) the prolate non-collective configurations become favored energetically for I>30 $\hbar$; (3) at spin I~40 $\hbar$, the valence space is essentially exhausted and a third minimum at $\epsilon_2 = 0.2$-0.3, $\gamma \sim 20°$ (involving $h_{9/2}$ and $i_{13/2}$ protons) becomes energetically competitive; (4) a superdeformed minimum is present at all spins with $\epsilon_2 \sim 0.5$ and $\gamma \simeq 0°$ and becomes yrast for I~50 $\hbar$. The prolate non-collective minimum originates from the alignment (with the symmetry axis of the nucleus) of <u>holes</u> in the high-j shells $\pi h_{11/2}$, $\nu i_{13/2}$ and $\nu h_{9/2}$ which drive the nucleus towards $\gamma = -120°$. The calculations reproduce the general features of the data fairly well. In particular, the coexistence of near-oblate rotational structures with single-particle, prolate non-collective states is accounted for, and the data indicate that the latter states become yrast for I~30 $\hbar$. Unfortunately, it is not possible to propose detailed configurations for the states reported here: most of the data cover a region where the single-particle states are not yrast and none of the highest spin states appears to be favored with respect to the others (which would facilitate an assignment). Nevertheless, a configuration can be proposed for the $41/2^-$ state at the bottom of the new sequence: $(\pi h_{11/2})^{-2}_{10}\nu[(i_{13/2})^{-4}_{10}(p_{3/2})_{1/2}]_{21/2}$. In our cranked Nilsson-Strutinsky calculations, this configuration results in a prolate non-collective shape (ϵ_2~0.1, γ=-120°) and a consistent interpretation in terms of a shape change from collective-oblate to non-collective prolate seems to emerge.

A paper reporting these results has recently been accepted for publication. Calculations are continuing with the aim of understanding the other rotational structures observed in this nucleus.

a.4. A Superdeformed Band in ^{192}Hg (R. V. F. Janssens, M. P. Carpenter, E. F. Moore, R. R. Chasman, I. Ahmad, P. B. Fernandez, T. L. Khoo, S. L. Ridley, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* M. W. Drigert,† and P. Benet‡)

Following the first observation of superdeformation in the mass A~190 region, a research program was initiated in order to address some of the questions raised by this first result. For example, the existence of an entire region of superdeformation needs to be established. Also, additional information on the properties of the superdeformed bands is very desirable. In contrast to the superdeformed bands in the A~150 region (where the decay out of the superdeformed band towards the ground state feeds several yrast states with varying intensities over an angular momentum range $\Delta I \sim 3\text{-}6\ \hbar$) the superdeformed band in ^{191}Hg was found to decay only to the $17/2^+$ yrast state. It was not possible to obtain a firm indication of the spins of the superdeformed states nor to assess whether the link between the superdeformed states and the yrast levels is statistical in nature as in the A~150 region or occurs only through a few specific transitions. Finally, the smooth increase of $J^{(2)}$ with rotational frequency $\hbar\omega$ was not understood. It is important to study this behavior in other superdeformed nuclei with the hope that it will contribute to the understanding of the underlying microscopic structure as is the case in the A~150 region.

A study was undertaken of the neighboring isotope ^{192}Hg. The states in ^{192}Hg were populated with the (^{36}S,4n) reaction using 162-MeV beams delivered by ATLAS and the γ rays were detected with the Argonne-Notre Dame BGO γ-ray facility. All experimental conditions were similar to those reported above for the experiments on ^{191}Hg. A total of 7.2×10^7 events were recorded and stored on magnetic tape for subsequent analysis.

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A new band of 16 transitions (Fig. I-3) extending in energy from 257 to 792 keV was observed in coincidence spectra generated from the γ-γ coincidence matrix. The band was seen in individual spectra gated on each transition. The band feeds the known levels up to 8^+ in the positive-parity yrast sequence and up to 9^- in the negative-parity band. The stretched-E2 character of all the transitions was established from the angular correlation measured at 34.5°, 90° and 145.5° with respect to the beam. The total flow through the band represents 1.9% of all transitions in ^{192}Hg. The energy spacing between γ rays in the new sequence decreases from 42.4 to 30.1 keV with increasing transition energy.

The average value of 36 keV is close to that reported for the superdeformed band in ^{191}Hg (37 keV). The corresponding average moment of inertia $J^{(2)}$ is 112 $\hbar^2$ MeV^{-1} and compares well not only with the average value for ^{191}Hg (110 $\hbar^2$ MeV^{-1}), but with the calculated value of Chasman (109 $\hbar^2$ MeV^{-1}). In addition, the band has many properties similar to those observed in ^{191}Hg (transition energies, intensity pattern,..) and is interpreted as a superdeformed band in ^{192}Hg; this represents the second case of superdeformation in this region. The spin of the lowest level in the superdeformed band was estimated to be 10 $\hbar$. This value follows from the deexcitation pattern out of the superdeformed band, the average entry spin into the yrast states (8 $\hbar$) and the assumption of a $\Delta\ell$=2 $\hbar$ angular momentum removal by the transitions linking the superdeformed states and the yrast line. The highest spin reported here then is 42 $\hbar$. Because of the uncertainties inherent to the procedure outlined above, the error on the proposed spins could be as large as 3 $\hbar$.

In order to gain direct information on the nuclear shape, transition quadrupole moments Q_0 were measured with the DSAM technique using a thick target. These measurements are currently still under analysis. However, preliminary results of this analysis indicate (i) that Q_0 remains essentially constant through the entire band with an average value of Q_0= 19$\pm$ 2 e.b. (ii) that the deformation is thus very similar to that reported for the superdeformed band in ^{191}Hg and (iii) that the side feeding into the superdeformed states is characterized by lifetimes similar to those of the superdeformed states themselves.

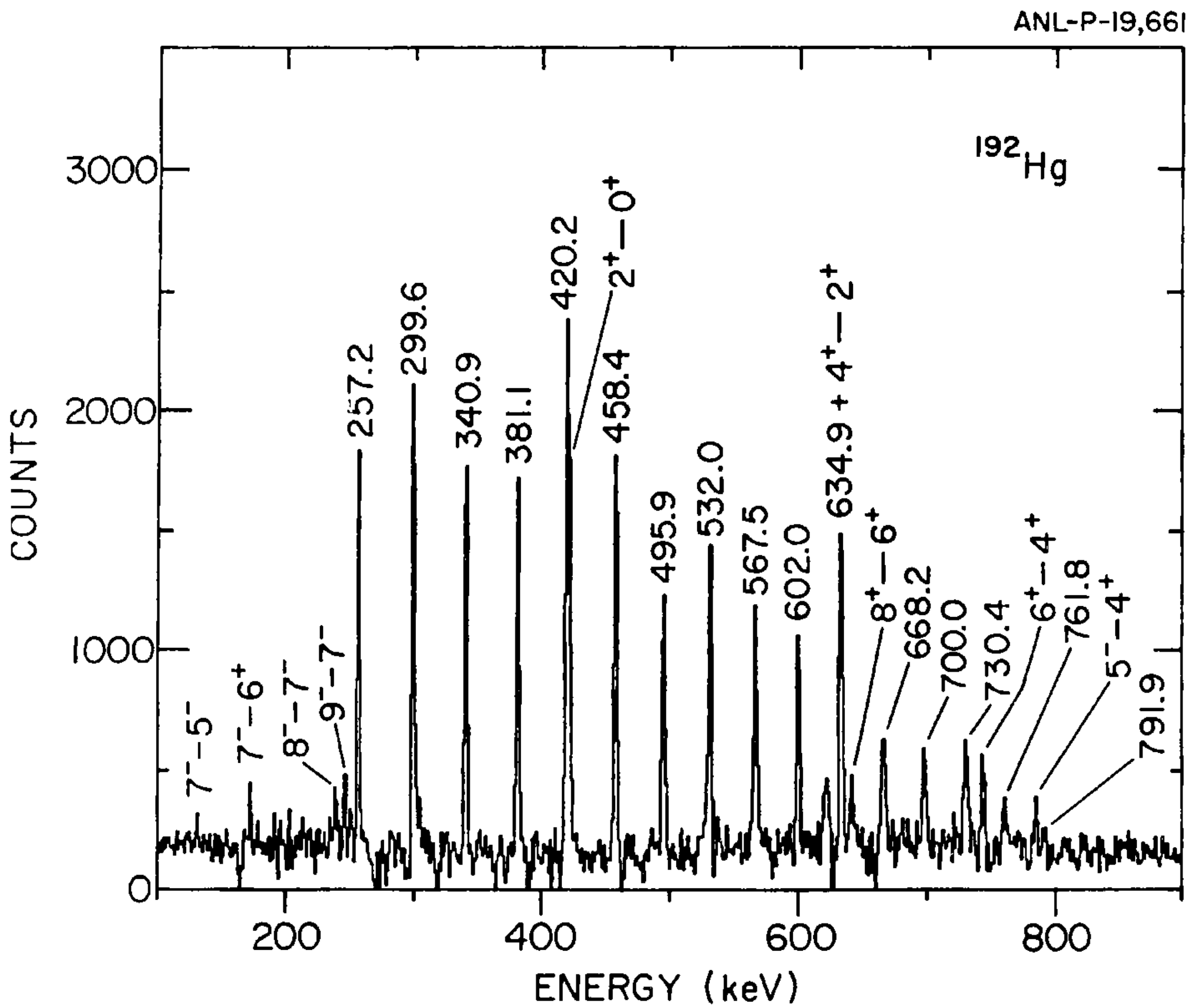

Fig. I-3. Gamma-ray spectrum in ^{192}Hg obtained by summing five clean coincidence gates on transitions of 257, 300, 341, 381, and 496 keV.

The evolution of the static and dynamic moments of inertia $J^{(1)}$ and $J^{(2)}$ derived for ^{192}Hg (Fig. I-4) show the following striking features: (1) $J^{(2)}$ is significantly larger than $J^{(1)}$ over a large frequency range, (2) there is a large (40%) monotonic increase of $J^{(2)}$ with $\hbar\omega$, and (3) the $J^{(2)}$ values for both Hg isotopes (A=192,191) are very close over the entire frequency range. All of these observations are not only a challenge for theory to explain, but also provide insight into the structure of nuclei at large deformation.

We have performed cranked shell-model calculations with the Warsaw-Lund code which uses a Woods-Saxon potential to calculate quasiparticle Routhians and $J^{(2)}$ values for superdeformed shapes in ^{191,192}Hg. The main results of these calculations can be summarized as follows: (1) neither deformation changes (as allowed by the lifetime measurements described above) nor the occupation of high-j single-particle intruder orbitals are sufficient to explain the pronounced increase in $J^{(2)}$, (2) the effects of pairing have to be taken into account, (3) in order to explain the similarity between the values of $J^{(2)}$ in ^{191}Hg and ^{192}Hg the value of the neutron pairing needs to be reduced considerably from the ground-state value, (4) the major contribution to the increase in $J^{(2)}$ is due to N=6 ($i_{13/2}$) protons.

A first report of our results on ^{192}Hg has been accepted for publication. As indicated above, the analysis of the lifetime data is still continuing.

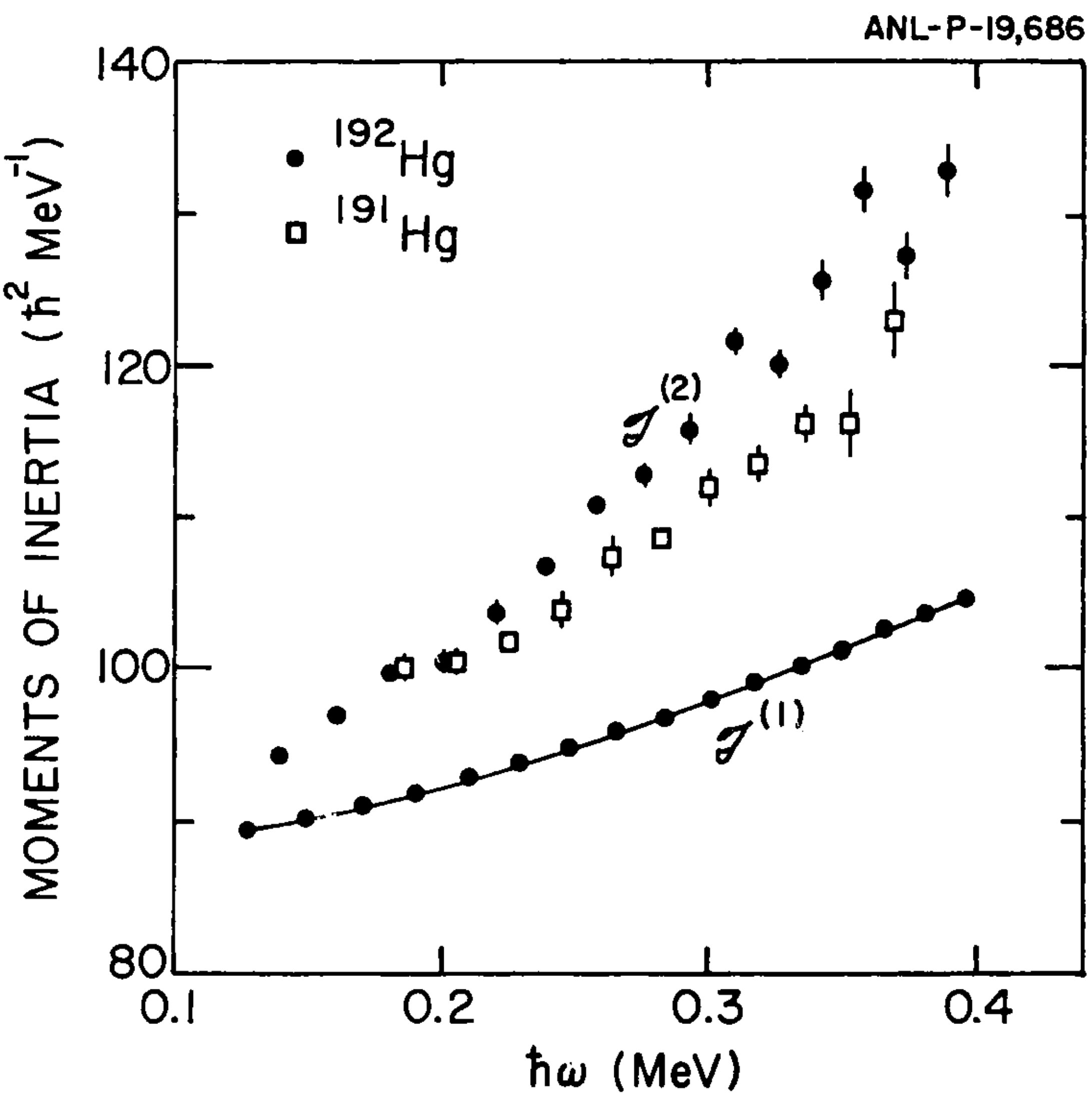

Fig. I-4. Static [$J^{(1)}=(2I-1)\hbar^2/E_\gamma$] and dynamic ($J^{(2)}=4\hbar^2/\Delta E_\gamma$) moments of inertia for ^{192}Hg. For comparison, the $J^{(2)}$ values for ^{191}Hg are also given. The data points are joined to guide the eye.

a.5. <u>Superdeformation in ^{190}Hg</u> (R. V. F. Janssens, M. P. Carpenter, E. F. Moore, R. R. Chasman, I. Ahmad, P. B. Fernandez, T. L. Khoo, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* M. W. Drigert,† and P. Benet‡)

Following the discovery of superdeformation in the nuclei ^{192}Hg and ^{191}Hg a search for superdeformed structures was also undertaken in ^{190}Hg in order to address some of the remaining open questions. One of particular importance concerns the excitation energy and the well depth of the minimum at large deformation as a function of mass. Cranked Strutinsky calculations predict that ^{192}Hg is a doubly-"magic" superdeformed nucleus due to the presence of large shell gaps in both the proton (Z=80) and neutron (N=112) single-particle spectra at the deformation β~0.55. It remains to be determined how many particles can be removed from ^{192}Hg before the shell effects are no longer strong enough to produce a deep secondary minimum or a minimum which is yrast at moderate spin (I~30-40$\hbar$).

We have identified the first superdeformed band (Fig. I-5) in ^{190}Hg with the ^{160}Gd(^{34}S,4n) reaction at 159 MeV. All experimental conditions were similar to those used for superdeformation searches in ^{191,192}Hg and are described in other sections of this document. The main results so far can be summarized as follows:
(1) a band of 11 transitions has been seen, (2) the assignment in ^{190}Hg comes mainly from the presence of the 2-0, 4-2 and 6-4 yrast transitions in the spectrum in coincidence with the superdeformed band, (3) the population intensity of the band is smaller by at least a factor of 2 with respect to the population of the superdeformed bands in ^{191,192}Hg (even though the initial angular momentum input and excitation energy are identical in all cases), (4) the deformation is as large as in the other superdeformed bands observed in our experiments. This was deduced from a DSAM measurement.

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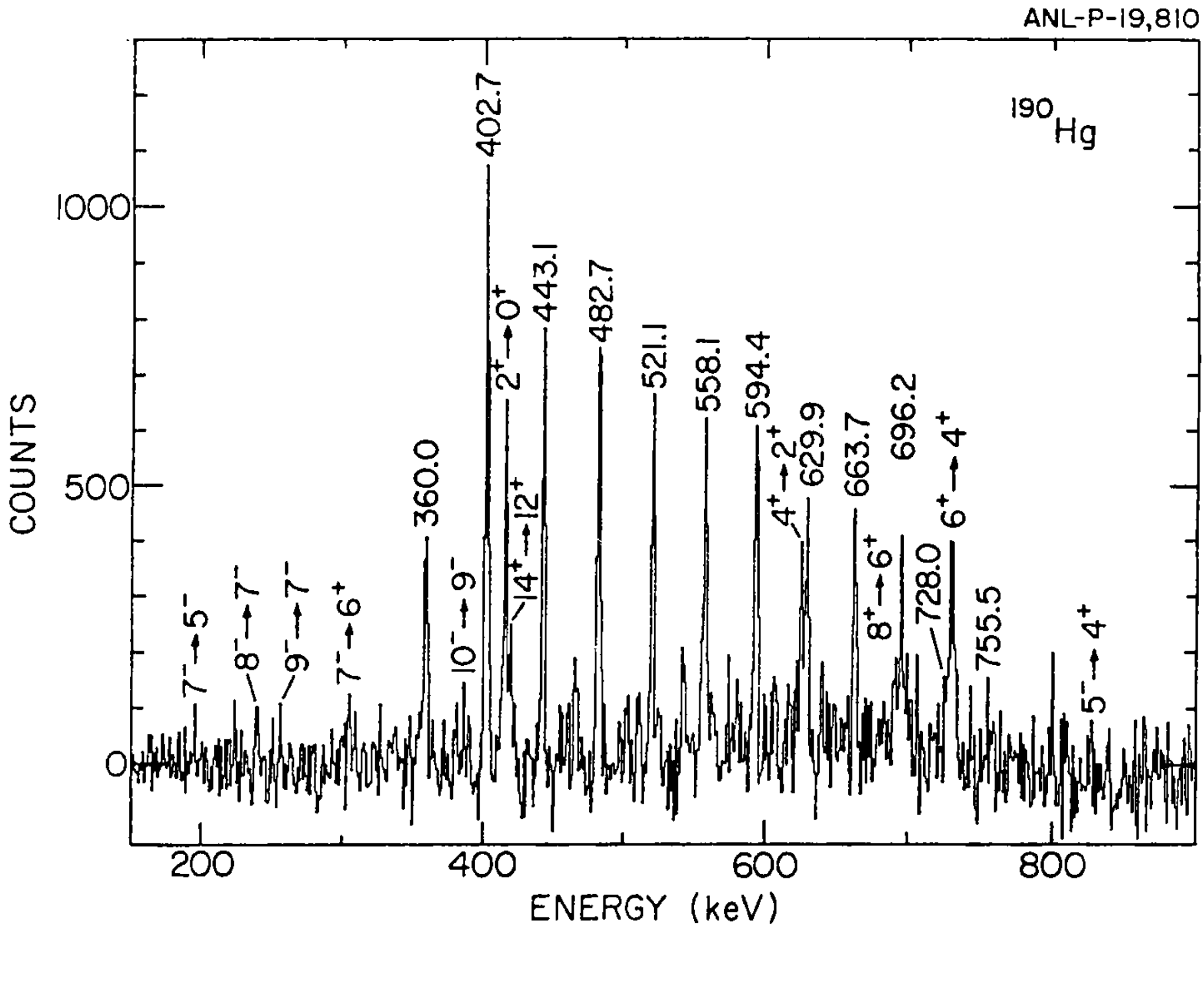

Fig. I-5. Gamma-ray spectrum in ^{190}Hg showing the deexcitation of a superdeformed band.

Our present results have been obtained in 4 days of beam time. The experiment was performed in two parts: in a first part a thin target was used and in the second part the thick target served to perform the DSAM measurement. In the near future we plan another experiment in order to extend the data set taken with the thin target. The objectives pursued are as follows: (1) the present data set is too limited to allow us to establish the decay towards the yrast line in great detail. As a consequence, it has not been possible so far to assign spin values to the superdeformed states and, hence, no static moment of inertia $J^{(1)}$ could be obtained. Comparisons between values of the static and dynamic moments of inertia are important; for example, they may give information on possible contributions from nucleon alignment(s) and on changes in pairing with rotational frequency. (2) The reason for the lower population intensity is not clear at the moment. At least two possibilities come to mind immediately: (i) as one lowers the mass number, the shell effects responsible for superdeformation might be weaker and the potential might not be as deep or might not be yrast any longer around spin 40; (ii) some of the flux may not be collected in the lowest (the yrast) superdeformed band but could be trapped in other discrete superdeformed bands. If the latter possibility materializes, one may hope to observe several excited bands. Their observation would allow us to obtain information on the single-particle configurations of importance in the superdeformed well.

a.6. Study of the Decay Out of the Superdeformed Bands in $^{191,192}Hg$
(M. P. Carpenter, R. V. F. Janssens, E. F. Moore, I. Ahmad, P. B. Fernandez, T. Happ, T. L. Khoo, S. L. Ridley, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* M. W. Drigert,† P. Benet,‡ and J. A. Cizewski§)

In the course of our experiments on superdeformation in the A~190 region, it became clear that some time delay (of the order of 1 ns or less) is involved in the link between the superdeformed states and the known low-lying yrast states. The experimental evidence was based mainly on the intensity of the yrast transitions in coincidence spectra gated on the superdeformed transitions in both ^{191}Hg and ^{192}Hg: the latter intensity was never 100% of the intensity in the superdeformed band, at least when thin targets were used. In order to study the properties of the deexcitation of the superdeformed states in greater detail a new experiment was performed where the time delay was studied.

In the experiment, the recoil-distance Doppler-shift method was used. The thin ^{160}Gd target was placed in front of a thick (50-mg/cm^2) Pb stopper foil. Measurements were performed for two target-stopper distances: 5 and 0.8 mm. The $^{160}Gd(^{36}S$, 4-5n) reactions were used with 167-MeV ATLAS beams. At this energy the superdeformed bands in both ^{192}Hg and ^{191}Hg are fed with appreciable strength. The γ rays of interest were obtained with the Argonne-Notre Dame BGO γ-ray facility. At present, the data on ^{191}Hg are the most promising: in this particular case the $17/2^+$-$13/2^+$ transition is the only one seen in coincidence with the superdeformed transitions. At the largest target-stopper distance, only a single peak corresponding to full Doppler shift was seen for this transition, but at the smallest distance two components were clearly visible. The ratio between the stopped and shifted components is consistent with a lifetime of about 0.5 ns. Unfortunately, this lifetime cannot be assigned as the lifetime of the superdeformed band head at the present time. Indeed, the data indicate that several yrast and near-yrast states have lifetimes of this order and it is quite possible that the link between superdeformed and yrast

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states proceeds through states with lifetimes of the same magnitude. The situation is identical for ^{192}Hg with the additional complication that in this case the decay out of the superdeformed band is known to spread over several yrast states, some of which have lifetimes that are again in the 0.2-0.8-ns range.

Clearly, more detailed measurements will be required in order to obtain the desired information. For this purpose, an improved recoil distance experiment is scheduled. A plunger device allowing us to obtain data at at least 5-8 more distances will be used. This experiment will also provide additional information on the lifetimes of the superdeformed states themselves.

a.7. Search for Superdeformed Structures in the Odd-Odd Nucleus ^{190}Au
(P. B. Fernandez, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, T. Happ, T. L. Khoo, E. F. Moore, F. L. H. Wolfs, K. B. Beard,* U. Garg,* M. W. Drigert,† P. Benet,‡ and L. L. Riedinger§)

So far, in the mass region A~190, superdeformed bands have been observed only in the Hg (Z=80) isotopes, even though they have been predicted to exist in neighboring isotopes, such as Pt (Z=78), Au (Z=79), and Tl (Z=81). If evidence for superdeformation were found in any of these other nuclei, it would provide clues towards the understanding of the underlying single-particle structure of superdeformed bands in this mass region.

In an attempt to search for superdeformation in the Au isotopes, we used the reaction ^{176}Yb(^{19}F,5-6n) to populate high-spin states in ^{190,189}Au. The 97-MeV ^{19}F beam delivered by ATLAS impinged on a stacked target of three 350-μg/cm^2 ^{176}Yb foils. γ-ray coincidences were measured using the Argonne-Notre Dame γ-ray facility. We collected 47x10^6 events in our coincidence matrix. So far, the preliminary analysis has not indicated the existence of superdeformed bands in the data. Since a fairly light projectile was used to induce the fusion reaction, it is possible that not enough angular momentum was

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brought into the compound nucleus to populate the superdeformed structures. We are currently analyzing the discrete γ-ray data on the normal deformed structures in $^{189,190}Au$, and will add significantly to the known level schemes in these nuclei.

a.8. Search For Superdeformed Structures in ^{191}Tl (M. P. Carpenter, R. V. F. Janssens, S. Pilotte,* L. L Riedinger,* C. H. Yu,* H. Q. Jin,* J. Lewis,* C. R. Bingham,* C. Baktash,† J. D. Garrett,† I. Y. Lee,† N. R. Johnson,† F. K. McGowan,† and J. McNeil†)

One common feature for all superdeformed bands observed in the Hg isotopes is the rise in the $J^{(2)}$ moment of inertia with increasing rotational frequency $\hbar\omega$. The major cause for this increase has been attributed to the alignment of a pair of $i_{13/2}$ (N=6) quasi-protons. The Tl isotopes offer the opportunity to test this hypothesis, since single-particle diagrams predict that the lowest-lying superdeformed bands for the Tl's in the A=190 region should be built on a single $i_{13/2}$ particle. If observed, such a band would block the $(\pi)i_{13/2}$ crossing suggested for the Hg superdeformed bands, and the resulting values for the $J^{(2)}$ are predicted to be nearly constant as a function of $\hbar\omega$.

In order to test this prediction, we have performed an experiment to look for superdeformation in ^{191}Tl. A superdeformed band has already been observed for the isotone of this nucleus, ^{190}Hg (N=110) (see Section I.C.a.5.). The experiment was carried out at the Holifield facility at Oak Ridge National Laboratory, utilizing the $^{159}Tb(^{36}S,^{4}n)$ reaction at 165 MeV. Nineteen Compton-suppressed Ge detectors were placed in the spin spectrometer to measure γ-ray coincidences, and the remaining 52 NaI detectors were used to record the sum energy and fold for each event. A γ-γ coincidence matrix has been created containing all events with a fold $\geq$ 9 (80×10^{6} events). Preliminary analysis of this matrix has indicated neither a presence of a superdeformed ridge in the γ correlations nor evidence for a discrete superdeformed band.

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a.9. <u>Excitation Function for the Superdeformed Bands in ^{191}Hg and ^{192}Hg</u>
(R. V. F. Janssens, I. Ahmad, M. P. Carpenter, P. B. Fernandez, T. Happ, T. L. Khoo, E. F. Moore, S. L. Ridley, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* M. W. Drigert,† and P. Benet‡)

First evidence was obtained for the existence of a new region of superdeformation near A=190 with the discovery of superdeformed bands in the nuclei ^{192}Hg and ^{191}Hg in experiments performed at ATLAS (see above). In both cases the intensity of the γ-ray flow through the bands was ~2% of the total intensity in the reaction channel of interest. This relatively high intensity compares rather well with that measured for similar collective structures in the A~150 region and raises important questions concerning the feeding mechanism responsible for this unexpected large population. In order to gain more insight into this problem, we have examined the population of the super- deformed bands in ^{191,192}Hg as function of beam energy for ^{160}Gd(^{36}S,4-5n) reactions. Results are summarized in Fig. I-6.

The experiments were carried out with the Argonne-Notre Dame BGO γ-ray facility at ATLAS. The ^{36}S-induced reactions on thin ^{160}Gd foils were studied for five energies between 154 and 172 MeV. At each beam energy extensive γ-γ coincidence measurements were performed.

The analysis of these data is still in progress. The following important results have already emerged: (1) the 3 superdeformed bands of ^{191}Hg are fed at 167 and 172 MeV only, the absolute intensity in the bands being smaller by a factor of ~2 at the lowest of these beam energies; (2) the superdeformed band in ^{192}Hg is seen at all beam energies between 154 and 167 MeV, and its intensity is essentially the same at all energies, except at the lowest energy where the intensity drops by ~60%; (3) the variation of the intensity in all the superdeformed bands as function of rotational frequency is very similar, i.e. the intensity is essentially constant at the lowest frequencies and drops at higher frequencies in the same way for both Hg isotopes; (4) for each superdeformed band the variation in intensity as a function of the rotational frequency does not change appreciably with beam energy; (5) the feeding of the superdeformed bands occurs at beam energies which are higher than those where the cross sections for the channels of interest peak.

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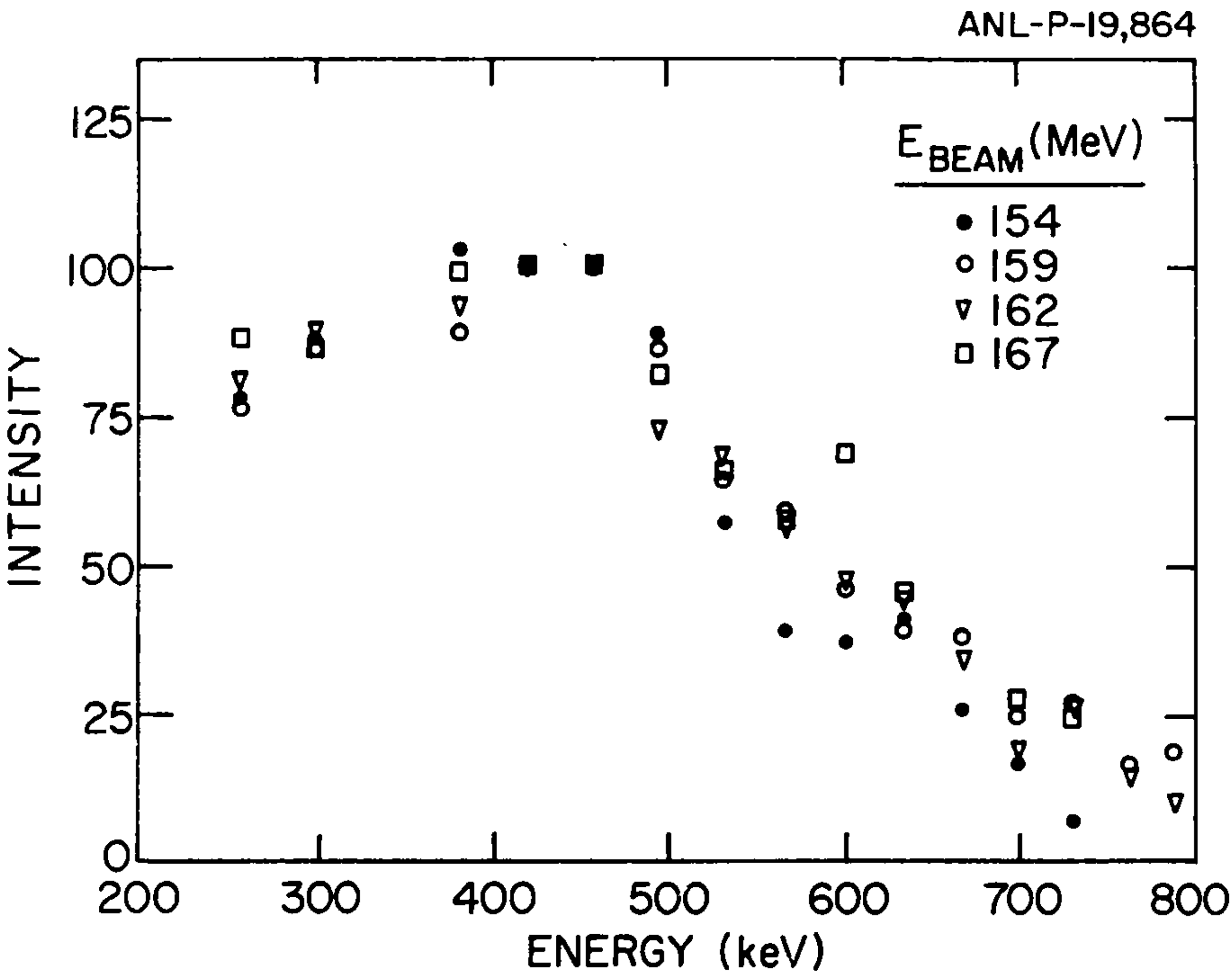

Fig. I-6. Intensities of superdeformed lines in 340-keV gate at different beam energies.

The analysis of these data is continuing. The results will be combined with those obtained from an analysis of the entry points for the superdeformed bands (described below) for a comparison with model calculations. The results will be prepared for publication. Further analysis will concentrate on the properties of the quasi-continuum γ radiation observed in coincidence with the superdeformed states.

a.10. Population of Superdeformed Bands, Competition with Fission and Constraints on the Well Depth (T. L. Khoo, E. F. Moore, S. L. Ridley, I. Ahmad, M. P. Carpenter, R. R. Chasman, P. Fernandez, T. Happ, R. V. F. Janssens, F. L. H. Wolfs, K. B. Beard,* D. Ye,* U. Garg,* P. Benet,† P. J. Daly,† Z. W. Grabowski,† and M. W. Drigert‡)

We have measured the entry points for superdeformed and normal states in ^{191,192}Hg at several beam energies with the ^{160}Gd(^{36}S,xn) reactions (see Fig. I-7). Compared with the normal states, the superdeformed bands have entry spins ~10 $\hbar$ higher and internal excitation energy ($U = E^* - E_{yrast}$) at least 2 MeV lower. Clearly the initial population for superdeformed bands originate from higher spin (I_{entry} = 29-42 $\hbar$) and is colder. In ^{192}Hg the mean spin at which the superdeformed band itself is populated is 30 $\hbar$ and this value does not increase with beam energy even though the entry spin increases. Thus the multiplicity of the precursor cascade increases when the initial ℓ_{max} of the evaporation residues increase. By comparison with calculated ℓ-distributions of evaporation residues, using CASCADE to compute the fission competition, we find that the initial population of the superdeformed bands originates from the tail of the evaporation-residue spin distribution. (There is a rapid onset of fission with increasing ℓ, which limits the survival probability of an evaporation residue at the highest ℓ (>40), and the depression in energy from the shell correction leading to the superdeformed well may increase the survival against fission.)

The mixing between superdeformed and normal states increases rapidly with energy above the barrier separating them. Thus, to a good approximation the entry point energy E_{entry} gives the energy of the barrier: $E_{entry}(I) \sim E_{SD}(I) + W_D(I)$. In this expression E_{SD} is the energy of the

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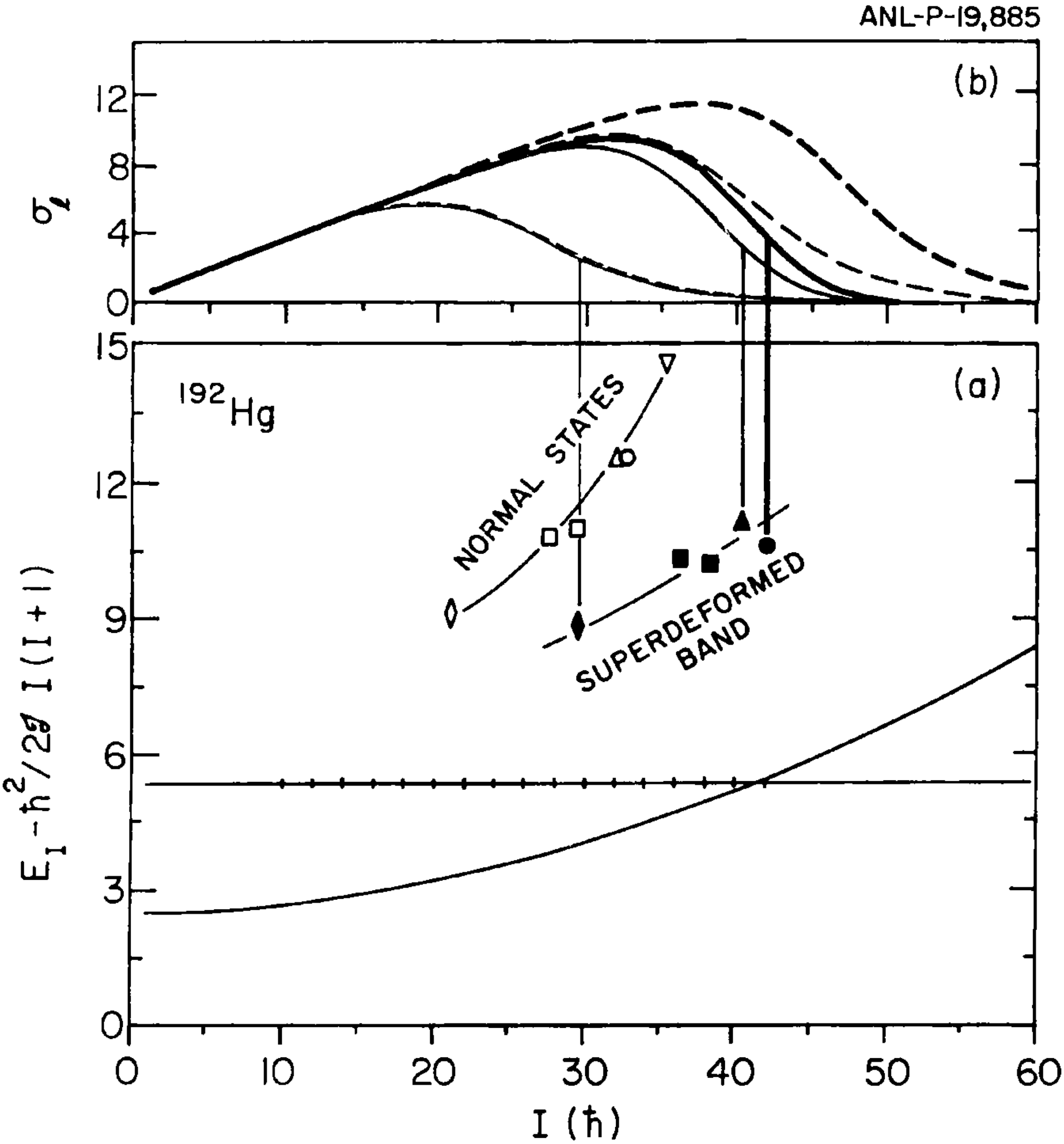

Fig. I-7. (a) Entry points associated with superdeformed and normal states; (b) calculated partial wave cross sections for compound nucleus and evaporation residues at beam energies of 154, 162 and 167 MeV.

superdeformed state. The measured entry points give constraints on the well depth W_D and its variation with spin. If E_{SD} were known, this method would provide a direct measure of W_D and, hence, of the magnitude of the shell correction. With an assumed value of $E_{SD} = 5.3 + 0.0051\ I(I+1)$ MeV, we obtain values of W_D between 3.4 and 5.7 MeV for spins of between 29 and 42 $\hbar$ for ^{192}Hg.

A paper is in preparation which reports these results and those on the feeding pattern of superdeformed bands. The next stage of this program is to extract the spectral shapes and energy-energy correlations associated with the γ cascade between the entry points and the feeding into the superdeformed bands. Results from these analyses will clarify the feeding mechanism of superdeformed bands and explain an unexpectedly rapid cooling which we have observed within the second well.

C.b. Superdeformed Nuclei: Studies Around A ~ 150

In previous years, research on the properties of superdeformation at Argonne had concentrated mainly on the A~150 region: our efforts had resulted in the discovery of a superdeformed band in ^{151}Dy. Current work aims at identifying the limits in proton and neutron number of the region where superdeformation occurs as well as on the study of the properties of nuclear states above the superdeformed yrast line.

b.1. Evidence for Superdeformation in the Z≃64, N≃80 Region

(I. Ahmad, R. R. Chasman, P. B. Fernandez, T. Happ, R. V. F. Janssens, T. L. Khoo, E. F. Moore, F. L. H. Wolfs, P. Benet,* P. J. Daly,* D. Ye,† K. B. Beard,† and M. W. Drigert‡)

Since the recent discovery of a rotational band corresponding to a superdeformed shape in ^{152}Dy, many attempts to predict and search for superdeformed nuclei in the A≃150 region have been reported. To date, superdeformation has been found only in several nuclei above the doubly-magic nucleus ^{146}Gd. Theoretical calculations by Chasman which have successfully predicted superdeformation in these nuclei, also calculate superdeformed minima for nuclei below ^{146}Gd. The two best candidates in this region are ^{144}Gd and ^{143}Eu.

With the ^{98}Mo(^{50}Ti,xn,xp) reactions at 219 MeV we have searched for superdeformation in the Gd and Eu nuclei of interest. The beams were delivered by the ATLAS accelerator to a 900-μg/cm^2 target and the γ rays were detected with the Argonne-Notre Dame BGO γ-ray facility. The γ-γ correlation matrix derived from the experiment exhibits a ridge-valley structure with a spacing consistent with what is expected for a superdeformed shape; the corresponding dynamic moment of inertia is $67.5 \pm 2.5\ \hbar^2$MeV^{-1}. Attempts to find rotational bands of discrete lines within this ridge were not successful. As a result, the assignment of the correlation pattern to a given nucleus is rather difficult since two reaction channels account for most of the γ-ray yield; the (^{50}Ti,4n) channel leading to ^{144}Gd and the (^{50}Ti,p4n) channel leading to ^{143}Eu.

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Attempts were made to discriminate between the two channels by selecting events with different sum energy and multiplicity in the BGO array. The correlated structure seems to be enhanced in a matrix where events belonging to ^{143}Eu are favored.

The analysis is continuing and concentrates mainly on the spectroscopy of the discrete states in the two nuclei under discussion. Also, an experiment where charged particles would be detected in coincidence with the γ rays of interest is being considered.

b.2. <u>Feeding of the Superdeformed Band in ^{152}Dy</u> (E. F. Moore, T. L. Khoo, R. V. F. Janssens, I. Ahmad, F. L. H. Wolfs, W. Ma,* K. B. Beard,† U. Garg,† D. Ye,† M. W. Drigert,‡ Z. W. Grabowski,§ M. Hass,¶ H.-J. Körner,|| and G.-E. Rathke,||)

Discrete-line superdeformed bands have been observed in a number of nuclei near A=150 with unexpectedly large intensities (on the order of 2% of the ground-state transition strength). We have performed experiments in an attempt to determine the mechanism responsible for this unusual population strength. The main aims were to measure the spectrum of quasi-continuum γ radiation associated with the superdeformed band and with the single-particle yrast band in ^{152}Dy and from this information, extract the average energy and spin (E_i, I_i) upon entry into each cascade.

It was found that in the reaction ^{120}Sn(^{36}S,4n)^{152}Dy at 172 MeV the average (E_i, I_i) for the single-particle and superdeformed bands were (52 $\hbar$, 34 MeV) and (70 $\hbar$, 35 MeV), respectively. These results suggest that the initial

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superdeformed band population is quite 'cold', with an excitation energy of only about 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 discrete-line superdeformed band.

Our data also suggest that the yield of statistical γ rays associated with the superdeformed band is significantly lower than that associated with the single-particle states, which is consistent with 'cold' population. The remaining quasi-continuum spectrum is composed almost entirely of stretched quadrupole (E2) γ radiation. The shape of the quadrupole component of the superdeformed quasi-continuum spectrum is very similar to that of the E2 'bump' associated with the single-particle band. This suggests that there is possibly some mixing between excited states in the superdeformed minimum and excited states in the low deformation minimum. Theoretical calculations are underway which will try to reproduce the average entry points and population properties of the two bands. We also hope to investigate the possible effect of mixing between superdeformed and 'normal' excited states on the feeding intensities and lifetimes of the superdeformed band.

b.3. Lifetimes and Sidefeeding Times of the Superdeformed Band in ^{152}Dy

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

The most convincing evidence that the bands in the A=150 region are indeed superdeformed comes from lifetime measurements. The lifetimes of states in the superdeformed band in ^{152}Dy have been previously measured by the group at Daresbury and were found to be consistent with a constant quadrupole moment of 19 ± 3 e.b. for the entire band. This value corresponds to a deformed shape with an axis ratio of about 2:1 (i.e. superdeformed). In their study, it was reported that the sidefeeding delays into the superdeformed band were extremely short, on the order of 1×10^{-15} sec. We have remeasured the lifetimes and

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sidefeeding times of the superdeformed band in ^{152}Dy with the aim of determining the relation between sidefeeding delays and the reaction used to populate the superdeformed states.

We used the reaction ^{120}Sn(^{36}S,4n)^{152}Dy at 172 MeV with the ^{120}Sn target evaporated onto a Pb backing in order to slow down and stop the recoiling residual nuclei. The Doppler-shift attenuation method was used to extract the lifetimes and sidefeeding times associated with the superdeformed band. Our data were found to be consistent with a constant quadrupole moment of 18±3 e.b. in excellent agreement with the previous results. We found that the best fits to our data were obtained when sidefeeding lifetimes on the order of $20\text{-}30\times10^{-15}$ s were included. These sidefeeding delays are significantly longer than those reported by the Daresbury group.

These results imply that there is some dependence of sidefeeding times on the reaction used to populate superdeformed states. From simple calculations, it can be shown that the ^{48}Ca beam used by the Daresbury group populates the residual ^{152}Dy nuclei closer to the expected superdeformed yrast line when compared to the ^{36}S beam used in our study. It is possible that in our reaction, excited states in the superdeformed minimum are populated more strongly than in the Ca induced reaction, thereby delaying the entry into the yrast superdeformed band. Theoretical calculations are in progress in order to reproduce this reaction dependence in terms of the population of excited superdeformed states as well as the mixing between superdeformed and normal deformed excited states. These results also suggest that a systematic experimental study of sidefeeding delays both as a function of projectile-target combination and bombarding energy should prove fruitful.

b.4. Excited States in the Superdeformed Minimum in ^{152}Dy

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

In addition to an yrast superdeformed band based on the lowest energy configuration in the secondary minimum weaker non-yrast superdeformed bands based on excited states in the secondary minimum in these nuclei can also exist. Very recently, excited discrete-line superdeformed bands have been found in some A=150 nuclei. We have performed experiments with the aim of populating non-yrast superdeformed states in ^{152}Dy.

We used the reaction $^{120}Sn(^{36}S,4n)^{152}Dy$ at 172 MeV. We could not find evidence for discrete-line excited superdeformed bands in our data. After the subtraction of Compton-scattered events from the two-dimensional E_γ - E_γ correlation matrix, a pronounced 'ridge-valley' structure parallel to the $E_{\gamma 1} = E_{\gamma 2}$ diagonal was observed. From the separation of the ridges, a dynamical moment of inertia $J^{(2)}$ consistent with superdeformation was extracted. While the first ridge (closest to the main diagonal) was strongly evident in the data, very little, if any intensity was seen in the second ridge. Roughly 70% of the intensity in the first ridge can be attributed to the yrast superdeformed band, with the remaining intensity peaked at γ-ray energies of about 1.3 MeV with a FWHM of about 0.25 MeV. From intensity balance arguments, it was found that not all of the non-discrete superdeformed flux could decay through the yrast superdeformed band.

These results imply that excited superdeformed bands in ^{152}Dy are populated in the sulfur-induced reaction. From the absence of second and higher ridges, one may deduce that the excited superdeformed bands are quite short, consisting on average of only two transitions. It is possible that some of this excited flux decays through the yrast superdeformed band, though certainly not all of it. Theoretical calculations are underway which will try to reproduce the intensities in the discrete superdeformed band as well as the non-discrete

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ridge-valley structure. It is hoped that information on the depth of the superdeformed well and the size of the shell gap responsible for the secondary minimum will result from these studies.

C.c. Hot Nuclei

In past years a substantial amount of data has been obtained on the properties of the compound-nucleus decay from investigations (i) studying the γ decay of the compound nucleus after particle evaporation by measuring the total γ-ray spectrum with Compton-suppressed Ge detectors or (ii) studying the origin of the suppression of neutron emission seen in some heavy-ion induced fusion reactions. Our current efforts are directed towards the understanding of these results by performing calculations within the framework of the statistical decay of the compound nucleus. These simulations try to incorporate the latest theoretical ideas about the nature of the states at high excitation energy and spin. Also, a first attempt was made to gain information on the time evolution of the pronounced collective E2 component of the quasi-continuum in ^{152}Dy via the measurement of magnetic precession. The spectral shape of the statistical component of the quasi-continuous spectrum was also measured in an experiment where the collective E2 component was strongly reduced by the use of an alpha-induced fusion reaction.

c.1. Time Evolution of the E2 "Bump" in ^{152}Dy Via Magnetic Precession Measurements (N. Benczer-Koller, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, F. L. H. Wolfs, M. Hass,* G. Kumbartzki,† P. Benet,‡ and K. B. Beard§)

The present work focuses on the time history of the so-called E2 "bump" which constitutes the major component of the quasi-continuous part of a γ-ray spectrum obtained in (H.I.,xn) fusion-evaporation reactions. This spectrum is a collection of many unresolved, collective E2 transitions resulting from decays of parallel rotational bands located above, but in the vicinity of the yrast line. Here, the time window generated by the action of the transient field acting on ^{152}Dy ions traversing a Gd layer is used as a clock to measure the time spent in the E2 bump and infer average B(E2)'s.

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High-spin states in ^{152}Dy were populated by the ^{76}Ge(^{80}Se,4n)^{152}Dy reaction using a 300-MeV beam from ATLAS. The ^{76}Ge target was deposited directly onto a 6.6-mg/cm^2 Gd foil. These thicknesses correspond to an average time window of 60-900 fs during which the Dy nuclei traverse the magnetized Gd layer and experience the transient field. The measurements were performed with the dedicated experimental setup described elsewhere in this document. The γ radiation was measured with the Argonne-Notre Dame BGO γ-ray facility. Transitions in ^{152}Dy were selected by appropriate gating on prompt and delayed radiation as detected in the BGO array. In particular, advantage is taken of a known high-spin isomer in ^{152}Dy for channel selection.

The experiment was performed late in 1989 and is currently under analysis. Preliminary results indicate sizable precessions for several strong discrete γ rays corresponding to transitions along the yrast line. The analysis now focuses on the continuum radiation. Future experiments are planned in order to explore other time intervals.

c.2. Calculations of Quasi-Continuum E2 Spectra in Dy Isotopes--Search for Signatures of Phase Transitions (T. L. Khoo, B. Stevens, Y. Alhassid,* B. Bush,* and R. Holzmann†)

Calculations based on the Landau theory of phase transitions or on the finite-temperature Hartree-Fock theory predict phase transitions in nuclei as the spin and/or temperature increase. Specifically, there is a predicted change from triaxial or prolate shapes to oblate ones which represent a new phase, as can be shown from symmetry arguments. The phase transition boundary has been mapped out as a function of spin and energy for ^{152,154,156}Dy. Fluctuations in a system with a finite number of particles may smear out the phase transition. Hence, it is interesting to find out if a signature of the predicted phase transition can be observed. The results will have ramifications for other predicted phase transitions in nuclei, e.g. the transition to a quark-gluon plasma or the liquid-gas transition.

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Experiments at Argonne have measured the quasi-continuum E2 spectra in $^{152,154,156}Dy$ and the results were published. In $^{152,156}Dy$ a single broad Gaussian-shaped component is observed, but in ^{154}Dy two peaks are observed, clearly signifying a structural change above the yrast line. The higher energy component in ^{154}Dy has a rotation-like property (the average transition energy increases with increasing spin), whereas the lower energy component has a vibration-like property (the average energy remains constant with spin).

By comparing the average γ-decay pathway with the phase diagrams, we find that it is only in ^{154}Dy that the cascade passes across the phase-transition boundary. This raises the question of whether the structure in the quasicontinuum E2 spectrum represents a signature of a phase transition. As the spin and energy decrease along the cascade pathway, the calculated moment of inertia rises and falls, peaking at the phase-transition boundary. This would have the effect of producing two separated peaks in the E2 spectrum. For a quantitative check of theory, we have started a program to calculate the spectra expected from the results of calculations based on the Landau theory of phase transitions, including the effects of fluctuations. The theoretical output is incorporated into a program we have used to calculate the quasi-continuum E2 spectra. The resulting spectra can then be directly compared to the experimental ones. The calculations are continuing and we expect to publish the results in the coming year.

c.3. Complete Spectroscopy and Shape of the Statistical Spectrum in ^{174}Hf

(T. L. Khoo, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, E. F. Moore, L. P. Farris,* M. J. Brinkman,* J. A. Cizewski,* R. G. Henry,* C. S. Lee,* J. J. Kolata,† K. Beard,† U. Garg,† D. Ye,† C. Kaplan,† D. Winchell,† and J. Saladin‡)

We have measured the γ spectra from ^{174}Hf with the (α,2n) reaction using beams from the Notre Dame FN tandem accelerator. The γ rays were detected in an array consisting of 6 Compton-suppressed Ge detectors and 14 BGO hexagons from the University of Pittsburgh. There are two separate aims for this experiment. First, we would like to identify the non-yrast levels in ^{174}Hf, in order to search for bands corresponding to multiphonon excitations. The (α,2n) reaction has in the past been very productive for identifying non-yrast bands, but has not been used in modern work with Compton-suppressed Ge detectors. From an experimental point of view it would also be interesting to find out what can be learned by the combination of these two tools, e.g. how high above the yrast line can one identify discrete levels. Second, we also want to extract the shape of the continuous statistical spectrum from the decay of ^{174}Hf. The shape of this component of the spectrum gives direct information on the γ-strength function. In addition, following a suggestion of Brink, we would like to explore if it can also give information on the quenching of pairing with increasing thermal excitation. It is preferable to measure the spectral shape of the statistical component using the (α,2n) reaction instead of (heavy ion, xn) reactions since the input angular momentum is not too high ($\ell<14\hbar$) with α-induced reactions. Thus, the E2 bump from continuum transitions preceding the discrete line decay (normally a dominant feature in reactions with large ℓ) is quite small. After subtraction of the discrete lines one would be left with primarily the statistical spectrum.

This work is part of the thesis of L. Farris and the data are being analyzed at Rutgers. Future work will depend on the results of this first experiment.

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c.4. Charged-Particle γ-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 array. Alpha particles and protons were detected in coincidence with discrete γ 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. The $^{12}C+^{144}Sm$ data are well described by statistical model calculations using the usual assumptions of a spherical compound nucleus with normal level densities. The $^{64}Ni+^{92}Zr$ data are not and explanations in terms of differences between the angular momentum distributions in the two channels have been ruled out on the basis of the available data. 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. These data are being prepared for publication.

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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.

C.d. Octupole Shapes in Nuclei and Other Spectroscopy Studies

Research on octupole shapes continued to focus on the new region of octupole deformation discovered at this laboratory three 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 are derived from experiments where γ-γ coincidences from fission sources are measured. This year, an experiment with very high counting statistics was performed with a ^{248}Cm source in order (i) to study the odd-even Ba and Ce isotopes around ^{144,146}Ba and ^{146}Ce where evidence for octupole deformation was found earlier as well as to (ii) test the limits of the new region of octupole deformation by establishing the level structure of other nuclei in this mass region. In this context, ^{142}Xe has been isolated and its level structure was found not to exhibit the characteristic pattern of competing E1 and E2 transitions expected for octupole deformation. Thus, this nucleus appears not to be octupole deformed, in contrast to predictions of theoretical calculations. Studies of reflection asymmetric shapes in the actinide region are also continuing with investigations in ^{223}Ac and neighboring Ac nuclei. Finally, it is worthwhile to mention that the measurements with the ^{248}Cm source also allowed the study of very neutron-rich nuclei near A$\simeq$100. These nuclei come as the complementary fragments to the Ba, Ce or Xe fragments mentioned above. Transitions in the very neutron-rich nuclei ^{103,104}Zr have been identified for the first time and rotational bands in $^{100-102}$Zr have been extended to spins up to 10 $\hbar$. The inferred ground-state deformations are among the largest known, with moments of inertia close to the rigid body values.

d.1. Level Structure of ^{142}Xe (I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, L. R. Morss, M. A. C. Hotchkis,* J. L. Durell,* J. B. Fitzgerald,* A. S. Mowbray,* W. R. Phillips,* P. Benet,† and D. Ye‡)

Recent mean-field calculations by Nazarewicz and collaborators indicate that nuclei with neutron number around 88 and proton number around 56 should have large octupole correlations at moderate spin. Measurements done on some Ba and Ce isotopes by this collaboration show an increase of octupole deformation with increasing spin, thus providing support to the theory. Also, the electric dipole transitions which have been reproduced by these calculations are found to be fast. We have now deduced the structure of ^{142}Xe (N=88) from the prompt γ-ray spectroscopy of nascent fission fragments produced in the decay of ^{248}Cm. The measurement was done with the Argonne-Notre Dame BGO γ-ray facility, which consisted of 10 Compton-suppressed Ge's, two LEPS, and an inner ball of 50 hexagonal BGO elements. By gating on the complementary Mo γ rays, we were able to identify ^{142}Xe transitions unambiguously. The levels form a quasi-rotational band (Fig. I-8), but there is no evidence for the negative-parity band and/or for any fast E1 transition. From the absence of this characteristic pattern we conclude that large octupole correlations are not present in this nucleus, contrary to theoretical predictions.

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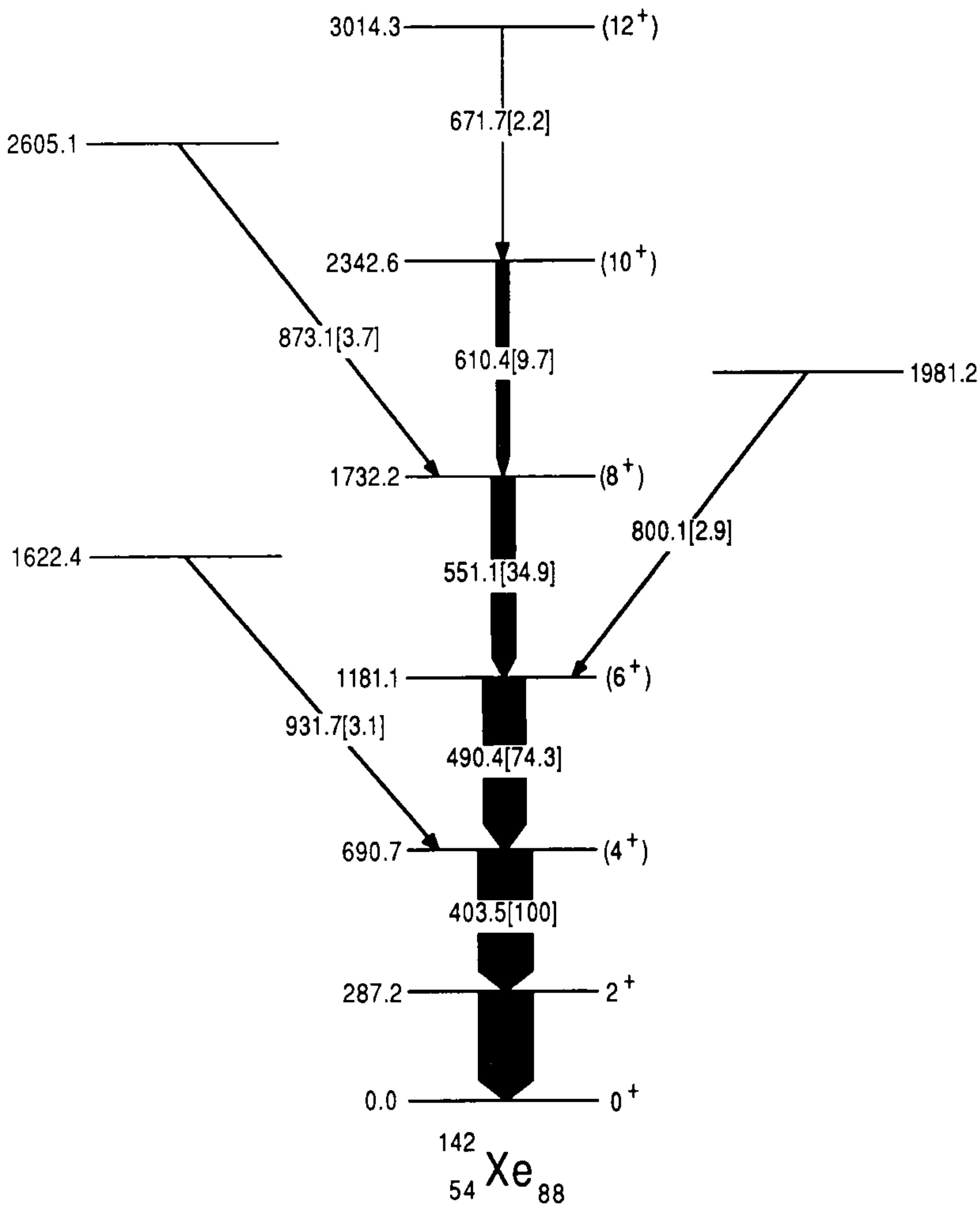

Fig. I-8. Partial level scheme for ^{142}Xe deduced from the present investigation. All levels have been observed for the first time. Numbers within square brackets denote relative gamma-ray intensities.

d.2. Structure of the Octupole-Deformed Nucleus ^{223}Ac (I. Ahmad, R. V. F. Janssens, R. Holzmann,* P. Dendooven,† M. Huyse,† G. Reusen,† J. Wauters,† and P. Van Duppen†)

Previous studies indicate that the maximum octupole deformation in the ground state occurs for Ac and Pa nuclei. Studies of level structures of ^{229}Pa and ^{225}Ac provide the best examples of octupole deformed nuclei. Theoretical calculations show that ^{227}Pa, ^{225}Pa, ^{223}Ac and ^{221}Ac have larger octupole deformation than ^{229}Pa and ^{225}Ac. At present the only means for the study of these nuclei seems to produce some parent isotopes by high-energy (50-70 MeV) protons and measure the radiations in the radioactive decay. We carried out the study of levels in ^{223}Ac by producing ^{227}Pa in the bombardment of a ^{232}Th target with 55-MeV protons at the Louvain-la-Neuve (Belgium) cyclotron, mass separating the mass-227 faction with the LISOL facility and measuring its radiations. From these measurements we have identified the $5/2\pm$ parity doublet in ^{223}Ac (Fig. I-9) and deduced a lower limit of 0.003 Weisskopf units for the rate of the E1 transition between the $5/2^-$ and $5/2^+$ states.[1] We also find attenuation in the Coriolis matrix element and M1 transition rate. The magnitude of the octupole deformation deduced from these data is found to be comparable to that in ^{225}Ac and not larger as predicted in calculations by the late G. Leander. The efficiency of the LISOL facility has recently been improved by a factor of 5, and tests have been performed with uranium targets. There has also been some improvement in the counting system. Because of these improvements, we plan to study the level structure of ^{225}Pa and ^{221}Ac. The nuclide ^{229}Np will be produced by the $^{233}U(p,5n)$ reaction and its alpha decay to ^{225}Pa and the alpha decay of the ^{225}Pa to ^{221}Ac will be investigated. Because of expected large alpha branches (>50%) for both nuclides, this experiment will provide enough information on ^{221}Ac and ^{225}Pa to deduce octupole deformation.

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[1] I. Ahmad, R. Holzmann, R. V. F. Janssens, P. Dendhooven, M. Huyse, G. Reusen, J. Wauters, and P. Van Duppen, Nucl. Phys. A505, 257 (1989).

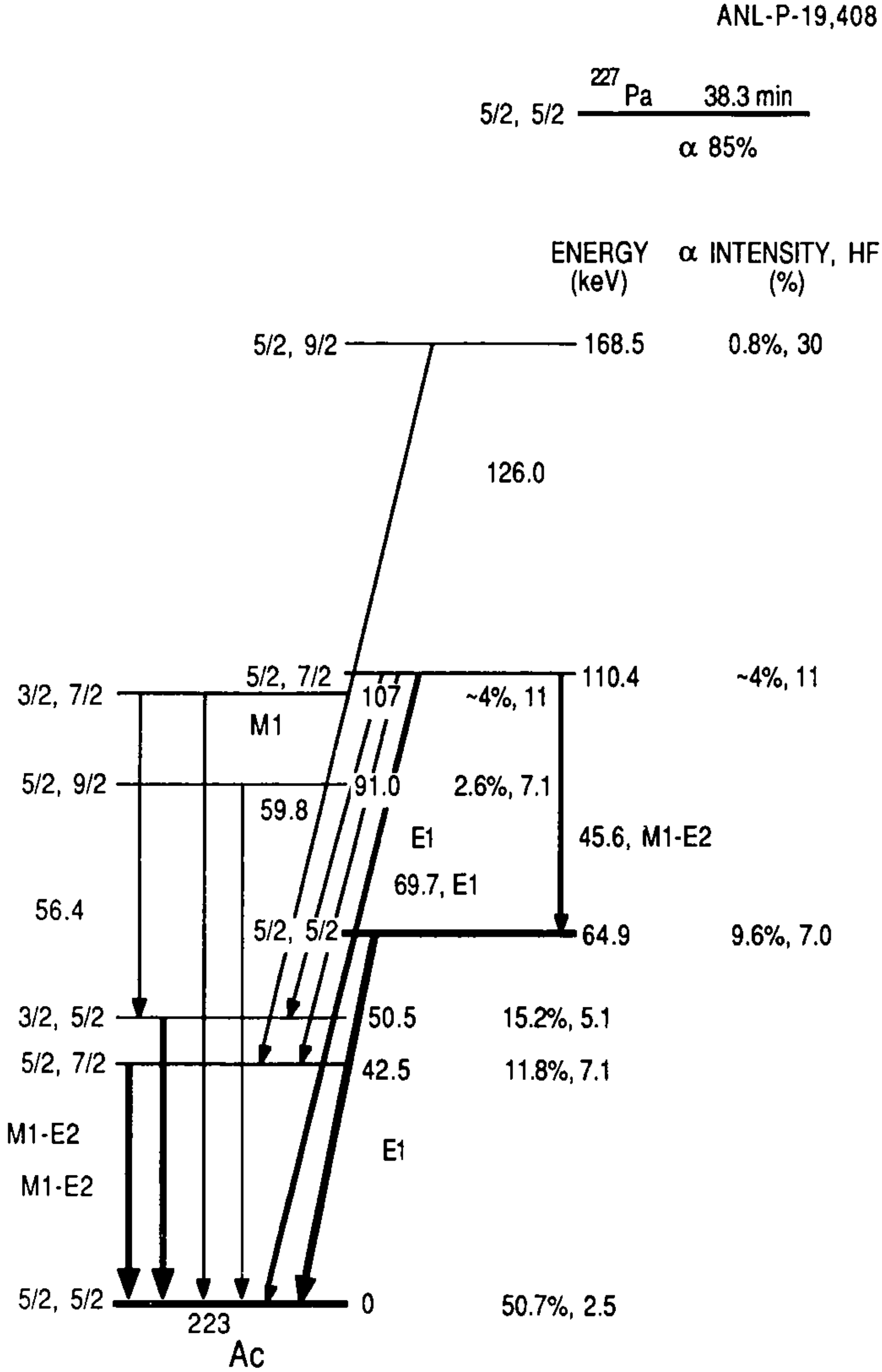

Fig. I-9. Level structure of ^{223}Ac deduced from the alpha decay study of 38-min ^{227}Pa.

d.3. Structures of the Very Neutron-Rich Nuclei ^{103}Zr and ^{104}Zr

(I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, L. R. Morss, M. A. C. Hotchkis,* J. L. Durell,* J. B. Fitzgerald,* A. S. Mowbray,* W. R. Phillips,* P. Benet,† and D. Ye‡)

Level structures of the very neutron-rich nuclei ^{103}Zr and ^{104}Zr have been studied for the first time up to spin 15/2 and 8, respectively. No information was available on these nuclei before the present measurements. The structures of these nuclei were deduced by measuring prompt γ-ray spectra of nascent fission fragments in the decay of a ^{248}Cm source. The experiment was performed with the Argonne-Notre Dame BGO γ-ray facility using a 5-mg ^{248}Cm source. The γ-ray setup for the present experiment consisted of 10 Compton-suppressed Ge detectors, 2 LEPS, and 50 hexagonal BGO elements. Data were recorded when γ rays were detected simultaneously in any two Ge or LEPS detectors and three of the BGO elements were required to fire as well. By gating on known γ lines of complementary Ba fragments, we were able to identify transitions in ^{103}Zr and ^{104}Zr (Fig. I-10). We also extended the known levels in ^{100}Zr and ^{102}Zr to spin 10 and the levels in ^{101}Zr to spin 19/2. In ^{104}Zr the 2^+ level is at a lower excitation than in ^{102}Zr, indicating a larger deformation. The β_2 deformations, as deduced from the energies of the 2^+ states, are 0.41 and 0.42 for ^{102}Zr and ^{104}Zr, respectively. These are among the largest deformations observed in nuclear ground states. Nilsson orbital assignments are made to the bands in ^{101}Zr and ^{103}Zr; the ^{103}Zr ground band and the excited ^{101}Zr band are assigned to the $5/2^-(532)$ Nilsson configuration. The present data show the influence of the occupancy of the $h_{11/2}$ orbital on deformation.

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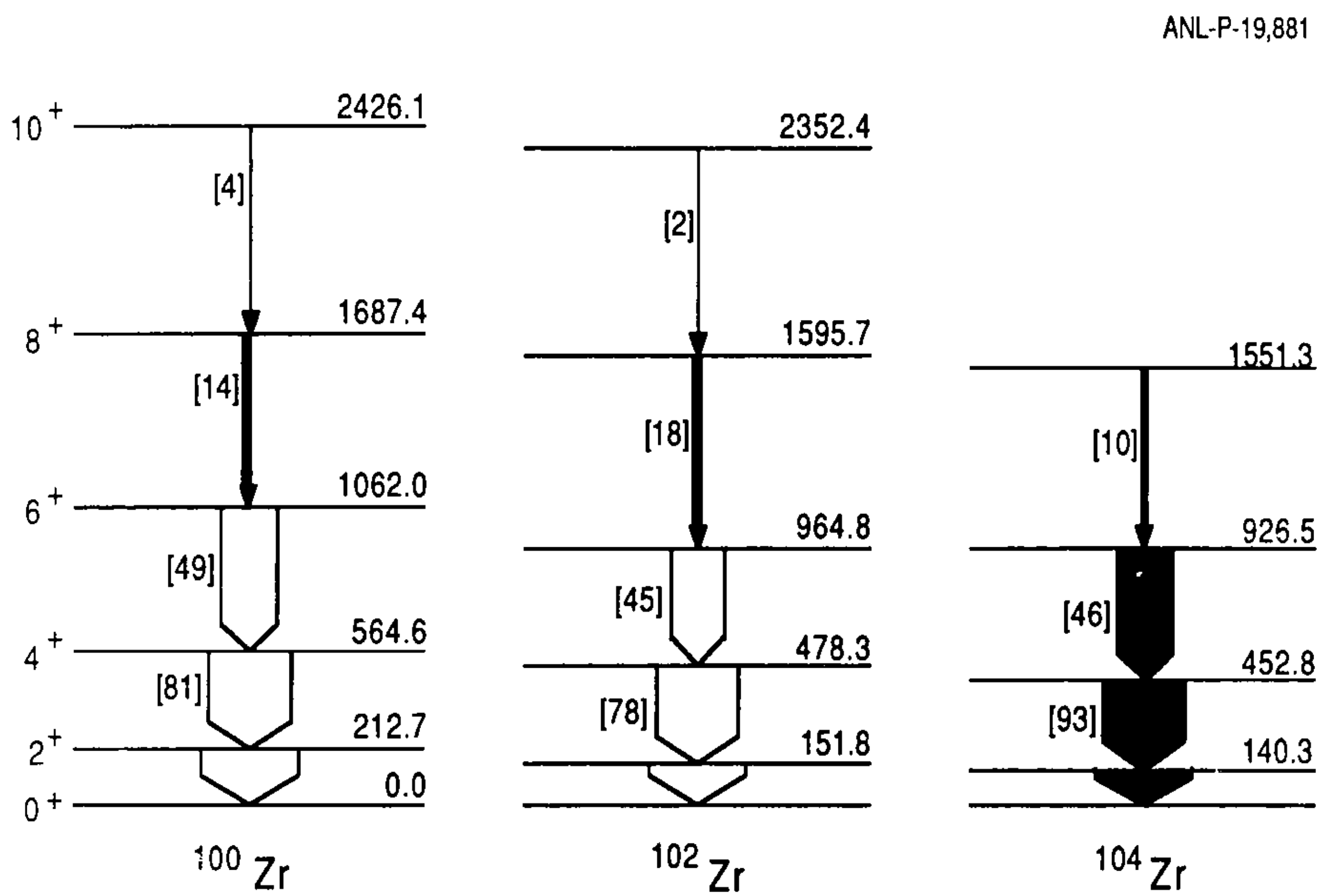

Fig. I-10. Level schemes of even-even Zr isotopes. New transitions observed in the present work are shown shaded. Relative gamma-ray intensities are given in square brackets.

d.4. The Structure of ^{136}Te (I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, J. A. Cizewski,* L. R. Morss, M. A. C. Hotchkis,† J. L. Durell,† J. B. Fitzgerald,† A. S. Mowbray,† W. R. Phillips,† P. Benet,‡ and D. Ye§)

The study of neutron-rich nuclei has traditionally been limited to those populated via beta decay of fission fragments, and therefore, spectroscopy of moderate spin excitations has been severely limited. However, recent measurements with the Argonne-Notre Dame BGO facility at ATLAS of the prompt γ rays emitted following spontaneous fission, have enabled the study of moderate spin excitations in neutron-rich nuclei, and have also helped to identify the most neutron-rich species of elements populated in spontaneous fission. We have identified, for the first time, the nucleus ^{136}Te following prompt ^{248}Cm fission. The γ-ray assignments to ^{136}Te were made by examining spectra gated on the Ru complementary fragments, and were confirmed in the ^{252}Cf measurements performed earlier by the same collaboration. These results are being examined in terms of the systematics of the Te isotopes and other N=84 isotones.

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d.5. Proton-Rich Shell-Model Nuclei with N≃82 (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 the first studies of some twelve N = 81, 82, 83 nuclei close to the proton drip line. We have found that in general the observed level spectra and transition probabilities can be explained quantitatively 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

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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 states 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 γ-γ coincidence data, both prompt and delayed, were acquired. Subsequently, the level schemes of the two N = 82 nuclei ^{149}Ho and ^{150}Er have been considerably extended in an 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 odd-odd N= 81 nuclei ^{146}Tb, ^{148}Ho 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 deexcites 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 have been working with R. D. Lawson on the interpretation of these results using Schiffer-True matrix elements and other formulations for the proton-neutron hole residual interactions. A paper reporting these results has been published.

d.6. Lifetime Measurements in ^{186}Pt (I. Ahmad, R. V. F. Janssens, E. F. Moore, T. L. Khoo, K. B. Beard,* U. Garg,* J. C. Walpe,* J. Wei,* M. Piiparinen,† and S. R. Shastry‡)

Using the recoil-distance Doppler-shift technique, lifetimes of levels in the yrast band of the nucleus ^{186}Pt have been measured up to spin 16^+ to further investigate the shape coexistence between bands corresponding to different nuclear shapes in this mass region. The ^{154}Sm(^{36}S,4n)^{186}Pt reaction was used and γ-ray spectra were obtained at several target-stopper distances using a plunger device in conjunction with the Argonne-Notre Dame BGO γ-ray facility. The central BGO array served as a multiplicity filter to ensure selection of high-spin states. The B(E2) values derived in the analysis increase from 97±9 WU to 270±40 WU in going from spin 2 to spin 10. This behavior is similar to that observed in earlier experiments for ^{184}Pt and might be indicative of two bands of different deformations mixing at low spins. The rise in B(E2) value from the 2^+ to 4^+ state is not as sharp in ^{186}Pt as in ^{184}Pt, however. An experiment studying the same phenomenon in ^{182}Pt will take place soon.

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D. ACCELERATOR MASS SPECTROMETRY (AMS)

The AMS program at ATLAS is currently in a transition stage from well-known tandem-based experiments to new experiments with the ECR source system. After the completion of a successful series of AMS experiments with the tandem-ATLAS system to detect ^{41}Ca ($T_{1/2}$ = 100,000 years) at natural levels in minerals and bones, last year's effort was concentrated on interpreting these data and assessing the conditions for the continuation of the quest to use ^{41}Ca as a dating tool, and for possible other uses.

With the ECR source, one starts with positive ions which allows one to investigate long-lived noble gas radioisotopes (^{39}Ar, ^{81}Kr, ^{85}Kr). Since noble gases do not form stable negative ions they cannot be measured at tandem accelerators and have not been explored by AMS. On the other hand, they are among one of the most-sought radioisotopes for tracing and dating studies since their chemical inertness greatly improves the understanding of their global distribution. We have started the development of AMS at the ECR source with a first exploratory experiment to assess the particular conditions required for this type of measurement.

At the Dynamitron, an AMS system to study the detection of very heavy helium-like isotopes was investigated with the goal to explore the possibilities of searching for "strange matter", a hypothetical form of matter consisting of roughly equal numbers of up, down, and strange quarks.

a. Status of Terrestrial $^{41}Ca/Ca$ Ratio Measurements
(W. Kutschera, I. Ahmad, P. J. Billquist, B. G. Glagola, R. C. Pardo, K. E. Rehm, and M. Paul*)

AMS measurements of $^{41}Ca/Ca$ ratios in a variety of terrestrial materials at four different laboratories (Argonne, University of Pennsylvania, GSI, Rehovot), revealed a rather complex picture of ^{41}Ca concentrations in nature. The $^{41}Ca/Ca$ ratios are distributed between about 5×10^{-16} to 5×10^{-14} with no apparent correlation of latitude, altitude, age or other factors. Taken at face value, the data do not encourage the development of a radiocalcium dating method. However, the present set of data represent the first generation of experiments with rather random choices of samples and methods. In addition, due to the very low natural abundance of ^{41}Ca and the general difficulty to get high Ca-beam intensities at tandem accelerators, most measurements have large statistical errors. Finally, there is a finite probability that some of the samples had an unknown amount of laboratory contamination from enriched ^{41}Ca material, and even global contamination with artificial ^{41}Ca from nuclear testing cannot be positively excluded. This situation signals quite clearly that a substantial improvement of sample selection, sample handling and $^{41}Ca/Ca$ ratio measurements is necessary to assess an accurate distribution of natural ^{41}Ca.

Preliminary tests with Ca beams at the ECR source and of the transmission through ATLAS with other beams indicate that an improvement of up to a factor 100 over the conditions for ^{41}Ca measurements with tandem injection may be expected. A particularly important improvement will be the use of CaO as sample material instead of the CaH_2 required in Cs-beam sputter sources, which is difficult to make and highly reactive. Although AMS with the ECR source is still in its infancy, it gives hope that it will eventually lead to a substantially improved AMS system for ^{41}Ca measurements.

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b. <u>Estimate of ^{41}Ca Production Through Nuclear Weapons Testing</u>
(B. Davids and W. Kutschera)

The global fallout of many long-lived radioisotopes (e.g. ^{3}H, ^{14}C, ^{36}Cl, ^{90}Sr, ^{137}Cs, ^{239}Pu) produced directly or via neutron activation in nuclear weapons testing, is well documented. In particular the ^{36}Cl 'bomb spike' has been measured by two AMS laboratories (Rochester, Zurich) in ice cores from Greenland. We have attempted to predict a possible ^{41}Ca bomb spike caused by neutron activation of calcium. Calcium is present at almost all nuclear test sites through corals of atolls in the marine tests and through rocks and soil in land tests. An estimate of the global inventory of artificially produced ^{41}Ca from these sources yields about 550 kg of ^{41}Ca. This has to be compared with an estimated amount of roughly 20 to 200 kg of natural ^{41}Ca in the top meter of exposed land area on earth. Using ^{90}Sr as a normalizing isotope, we estimate that ^{41}Ca could be present in ice cores at a concentration of up to 10^8 atoms/kg ice. This is comparable in magnitude with the ^{36}Cl concentration and should be measurable by AMS.

c. <u>Constraints on Predicting Cosmic-Ray Production of ^{41}Ca on Earth</u>
(K. Kavana and W. Kutschera)

The main natural process of ^{41}Ca production is the capture of cosmic-ray secondary neutrons in ^{40}Ca near the surface of the earth. Variations of ^{41}Ca/Ca ratios are expected since the detailed composition of rocks and soil determine the local ^{41}Ca production rate and erosion rates influence the saturation values. Without erosion, one estimates saturation values for ^{41}Ca/Ca ratios of 10^{-15} to 10^{-14}. Since conditions vary greatly, it is likely that only systematic measurements of ^{41}Ca/Ca ratios in geologically 'well-behaved' rock formations will reveal an accurate picture of the ^{41}Ca distribution. Besides neutron capture, there are a few other possible production mechanisms for ^{41}Ca. We have estimated the spallation of heavy Ca isotopes and of Ti and Fe by the hadronic component of cosmic rays (protons and fast secondary neutrons) in major igneous and sedimentary rock types. Relative to the ^{40}Ca(n,γ)^{41}Ca process, spallation contributes at most a few percent. In the atmosphere, we estimate that the average ^{41}Ca production rate by spallation of Kr is below 10^{-7} at/cm^2/s which probably contributes less than 1% to the global ^{41}Ca inventory. Another process yet to be studied is the production of ^{41}Ca from alpha and ^3He reactions on argon. It is possible that solar flares, which have very high fluxes of these particles, produce non-negligible contributions to the natural ^{41}Ca inventory on earth.

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

There are three long-lived noble gas radioisotopes which are potential candidates for AMS: ^{39}Ar ($T_{1/2}$ = 269 yr), ^{81}Kr ($2x10^5$ yr) and ^{85}Kr (10.7 yr). Their isotopic ratios in the atmosphere are: $^{39}Ar/Ar = 8.1x10^{-16}$, $^{81}Kr/Kr = 5.3x10^{-13}$, and $^{85}Kr/Kr = 1.3x10^{-11}$ (1984), $3x10^{-18}$ (pre-nuclear). From a geochemical point of view, ^{81}Kr would be an ideal tracer, well mixed in the atmospheric krypton reservoir, which is of constant size and has essentially no sources or sinks. Of particular interest would be the dating of very old ice from Greenland and Antarctica. The high ^{85}Kr content of the atmosphere is due to releases in nuclear fuel reprocessing and could be useful as an artificial tracer for global transport phenomena. The very low $^{39}Ar/Ar$ ratio is due to the relatively high content of argon in the atmosphere (0.9%). Although such low ratios are presently at the limit of AMS sensitivities, the high beam intensities of the ECR source may make detection at natural levels feasible.

A first exploratory experiment to understand the setup for ^{39}Ar detection with the ECR-ATLAS system was performed. The entire system from the source through the positive-ion injector and ATLAS to the gas-filled magnetic spectrograph in target area III was tuned with $^{13}C^{3+}$ ions to an energy of 40 MeV. A total transmission of 5% was established for this condition. Since ions with the same M/Q are identical in all aspects of acceleration and beam transport, these ions served as a first-order approximation to the acceleration of 120-MeV $^{39}Ar^{9+}$. In addition, a fine-tuning of the system with $^{39}K^{9+}$ ions was performed to understand flight-time corrections between $^{13}C^{3+}$ and $^{39}Ar^{9+}$ due to finite M/Q differences and the appearance of other ions with the same M/Q in the spectrograph (e.g. $^{26}Mg^{6+}$, $^{52}Cr^{12+}$, $^{65}Cu^{15+}$, $^{78}Se^{18+}$). The test showed that an

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AMS setup of the ECR-ATLAS system for ^{39}Ar is possible and the next step will be the actual detection of this radioisotope from argon samples irradiated in a reactor to produce ^{39}Ar/Ar ratios in the range of 10^{-13} to 10^{-11}.

e. A Laboratory Search for Strange Matter (P. B. Fernandez, J. Gehring,* W. Kutschera, J. F. Last, J. P. Schiffer, P. Sigmund,† and M. Paul‡)

Strange matter can be thought of as a "nucleus" made up of roughly equal numbers of up, down, and strange quarks. Theoretical calculations by E. Farhi and R. L. Jaffe indicate that for a certain range of values of the relevant QCD parameters (the bag constant B, the strong coupling constant α_c, and the strange quark mass m_s) strange matter may be absolutely stable, and, therefore, the true ground state of a system of baryons. The conditions for production of strange matter could possibly be achieved in the later stages of the evolution of massive stars. Right after a supernova explosion, the pressure in the core of the neutron star remnant can be high enough to cause quark deconfinement and the subsequent formation of a strange-matter star. If this strange star were to collide with another star (a possible scenario in binary systems), strange matter aggregates, with baryon numbers anywhere in the range $10 \lesssim A \lesssim 10^7$, could survive the collision and become part of the interstellar gas. This mechanism for strange-matter formation could explain some astrophysical occurrences, such as Centauro cosmic-ray events in which the primary seems to fragment exclusively into hadrons.

Since strange-matter nuggets, or strangelets, are composed of roughly equal amounts of up, down, and strange quarks, their characteristic charge-to-mass ratio is much lower than for normal matter. Strangelets would then look like very heavy isotopes of a given element, and could in principle have a very different chemistry than normal atoms, making it hard to identify terrestrial sites to search for strange matter. A simplification occurs if the charge of

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the strangelet corresponds to a closed electronic shell, making the resulting strange atom chemically inert, and likely to follow the same behavior as the noble gases (helium, neon, argon, krypton, and xenon). Under this assumption, we proposed to search for terrestrial abundance of strange matter in noble gases.

Our experiment exploited the very low charge-to-mass ratio of strangelets. We used a 4-MeV Ar beam from the Dynamitron facility; the beam was transported down the 0° beam line to our scattering chamber, where it impinged on a 3.4-mg/cm^2 Al foil. This foil was thick enough to stop the argon beam, but not the strange nuclei, since their lower charge would presumably result in a lower stopping power. A 300-μ, 150-mm^2 silicon detector was placed at 0° behind the Al foil to detect the slowed-down strangelets. Except for an ≈ 50-G magnetic field in the switching magnet that was used to deflect protons and other high-q/m components of the beam which would not have been stopped in the Al foil, the beam transport was done using only electrostatic elements, thus ensuring that the different low-q/m components would not be significantly scattered before hitting the Al foil.

We had two runs to explore the feasibility of the experiment. We found that there were light components of the beam which were neutral (e.g. H_2, H_3, etc.) in the region where the 50-G field was applied and, therefore, proceeded undeflected and unstopped by the Al foil, to strike the silicon detector. Efforts to reduce this background have proven unsuccessful so far.

f. On the Production of a Beam of the Long-Lived 16+ Isomer In ^{178}Hf
(W. Kutschera, I. Ahmad, W. J. Childs, R. V. F. Janssens, R. C. Pardo, and L. F. Mausner*)

The long-lived high-spin isomer of ^{178}Hf, with a half-life of 31 years and a spin of 16+, presents a unique opportunity for a projectile and/or target in nuclear and atomic physics. It would allow one to study high-spin phenomena in a new way. The total activity involved in making a beam does not present an insurmountable problem for a heavy-ion accelerator environment. We have estimated that with 10 millicurie of ^{178m}Hf, distributed in a suitable matrix source material, one might be able to deliver a beam of 10^7 atoms/s for about a month of running time.

In order to find the best way of producing ^{178m}Hf, we bombarded a stack of five 0.8-mm thick Ta foils with 190-MeV protons at the Brookhaven Linac Isotope Production Facility. After a several-month cooling period, we found production cross sections of about 40 and 200 microbarn for the lowest two energies of 46 and 92.5 MeV, respectively, by measuring the decay gamma-ray cascade with the Argonne-Notre Dame BGO array. Although this looks encouraging, there are drawbacks of this reaction. Several unwanted Hf radioisotopes are produced in large quantities. Particularly unpleasant is ^{172}Hf with a half-life of 1.87 years. Most important, however, is the production ratio of the isomer relative to the ground state of ^{178}Hf. A novel isomer separation technique by selective laser deflection is contemplated, but one certainly wants to optimize this ratio in the production process. To this end we are planning to investigate the reaction ^{176}Yb(α,2n)^{178m}Hf which promises to constitute the most selective production of the 16+ isomer.

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E. OTHER TOPICS

In addition to the research presented in the previous four sections some effort has been devoted to a variety of other heavy-ion research. The measurement of the γ width of the 5.17-MeV state in $^{14}O^*$, which is of importance for the hot CNO cycle, has been completed and the analysis of the data is well underway. In another experiment of dielectronic recombination on channeled ions it was shown that crystalline targets can provide a close approximation to an ideal electron gas in the study of ion-electron collisions. The widths of the resonances for dielectronic recombination were found to be almost an order-of-magnitude smaller than in previous experiments. The calculations of a possible condensed crystalline state in confined systems of cooled heavy ions have been continued and first studies to detect these structures at the IUCF proton storage ring have begun. Another experiment searched for charged particles (p,^3H) from the $^2H(^2H,p)^3H$ reaction in an electrolytic cell with deuterium-loaded Pd electrodes resulting in an upper limit which is orders-of-magnitude too low to explain excess heat production, which was claimed to occur in some experiments.

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

Explosive hydrogen burning occurs in astrophysical environments where the temperatures and densities are sufficiently high so that radiative proton capture can successfully compete against radioactive β decay. In such environments (e.g. supermassive stars, accreting neutron stars, nova and supernova explosions), the rate for $^{13}N(p,\gamma)$ can become faster than the ^{13}N β-decay rate, turning the CNO cycle into the β-limited or hot-CNO cycle:

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

Both the dynamics of the stellar environment and the relative abundances of the nucleosynthetic yields are greatly affected by the operation of the hot-CNO cycle: the rate of energy generation of the cycle becomes significantly faster and basically temperature independent, and the abundance ratio of the β-decay daughters ^{14}N and ^{15}N is substantially modified. The temperature and density conditions for the onset of the hot-CNO cycle depend on the cross section for $^{13}N(p,\gamma)$ for $E_p < 1000$ keV.

So far, the short half life of ^{13}N ($\simeq$ 10 min) has made it impossible to perform a direct measurement of the cross section using either a radioactive ^{13}N target or beam. An alternative approach is to determine the cross section indirectly. The low energy $^{13}N(p,\gamma)^{14}O$ reaction cross section is dominated by the low-lying s-wave resonance to the 5.17-MeV, 1^- first excited state in ^{14}O, and should be well described by a single-level Breit-Wigner expression. The input parameters for this computation are the resonance energy E_R = 541 keV, the total width Γ = 38.1 ± 1.8 keV, and the γ-width Γ_γ. This last quantity can be determined from a measurement of the γ-ray branching ratio Γ_γ/Γ.

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At ATLAS, we have used the $^{1}H(^{14}N,^{14}O)n$ reaction at a beam energy of 175 MeV to populate the ground and first excited states in ^{14}O. Due to the forward focussing kinematics, the recoiling ^{14}O nuclei were full accepted by an Enge split-pole spectrograph, and were then detected in the Bragg-curve detector system located in the focal plane of the spectrograph. The less-rigid $^{14}O_1$ (populating the 5.17-MeV level) was successfully separated from the ground state $^{14}O_0$. At the same time, an array of NaI crystals surrounding the target detected the 5.17-MeV γ ray from the decay of $^{14}O_1$. From this experiment we will be able to obtain both a singles and a coincidence measurement of the branching ratio Γ_γ/Γ, in terms of the ratio of production cross sections for the ground and first excited states in ^{14}O.

To determine the production ratio, we carried out an experiment at the University of Washington in Seattle. We used a pulsed 12.5-MeV proton beam to populate the states of interest in ^{14}O through the reaction $^{14}N(p,n)^{14}O$, at the same center-of-mass energy as in the ATLAS experiment. We measured the neutron angular distribution for both the ground and first excited states in ^{14}O, for $20° \leq \theta_{lab} \leq 90°$. From this experiment, it will be possible to compute the ratio of production cross sections $\sigma(^{14}O_0)/\sigma(^{14}O_1)$, which combined with the ATLAS results will yield the γ-ray branching ratio Γ_γ/Γ. Analysis of the data from both experiments is currently underway.

b. Dielectronic Recombination on Channeled Ions

(A. Belkacem, E. P. Kanter, K. E. Rehm, K. H. Berkner,* E. Bernstein,† M. W. Clark,† S. M. Ferguson,† W. G. Graham,‡ D. Schneider,§ and J. A. Tanis†)

When fast heavy ions are channeled between the ordered rows of a crystal lattice, small-impact-parameter collisions with target atoms are reduced considerably. As a result, atomic excitation and charge-changing probabilities are altered significantly from expectations based on collisions in amorphous solids or in gaseous targets. Even more striking, hyperchanneled ions (ions whose low transverse momenta cause their motions to be limited to a single axial channel) exhibit an anomalously high probability for maintaining their initial charge state in moving through crystals many times thicker than amorphous targets of equilibrium thickness. These so-called "frozen" charge states represent that fraction of the beam which is hyperchanneled and thus avoid close collisions with the target atoms.

During the past year, we conducted two experiments exploiting the good energy resolution of ATLAS and using the phenomenon of frozen charge states to study dielectronic recombination (DR). In the DR process, single-electron capture is accompanied by simultaneous (correlated) projectile excitation via the electron-electron interaction. This process is the inverse of the Auger effect and is highly dependent upon electronic correlations in the intermediate excited state. Accurate measurements of state-selective DR cross sections can thus provide stringent tests of atomic structure calculations in heavy few-electron systems. The physical nature of channeling suggested that it might be possible to observe DR in a crystalline target, approximating to a high degree, capture in an electron gas.

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In our first experiment,[1] we carried out high-resolution measurements of the energy loss and corresponding charge-changing probabilities of 267-320-MeV Ti^{19+} and Ti^{20+} ions channeled along the <110> axis of a thin (400 Å) gold crystal (see Fig. I-11). By separating the hyperchanneled particles through their energy loss (with the split-pole spectrograph), we found that the best-channeled ions (see Fig. I-12) demonstrated dramatically enhanced probabilities for electron capture in the region of projectile velocity corresponding to the capture of free electrons. We attributed this phenomenon to dielectronic recombination. The widths of the observed resonances were exceedingly narrow (nearly an order of magnitude sharper than those observed previously in similar experiments on H_2 targets). In fact the resonance widths we find are even narrower than the DR structures observed with cooled ions in an electron-beam ion trap (EBIT).

The extremely high resolution of this experiment, however, presented a new puzzle with respect to the transition energies. A comparison of the resonance energies observed with both Ti^{19+} (Fig. I-13) and Ti^{20+} (Fig. I-14) demonstrated a shift towards higher Auger energy for the more highly-screened Ti^{19+} ion, as expected. Furthermore, the magnitude of the shift (about 60 eV) agrees quite well with theoretical estimates. However, both resonances are shifted by about 75 eV (on an absolute scale) to energies higher than anticipated from theory. The shifts observed in our measurements for Ti ions are more than an order-of-magnitude greater than the effects of dynamical screening and at present this behavior is not understood. In order to elucidate the Z-dependence of this energy shift, we conducted a second experiment to reproduce this effect with He-like and Li-like Ca ions. Because of difficulties with the beam-energy resolution, the resonance widths were quite broad, however it appears that the energy shift is comparable to that observed with Ti.

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[1] A. Belkacem et al., Phys. Rev. Lett. 64, 380 (1990).

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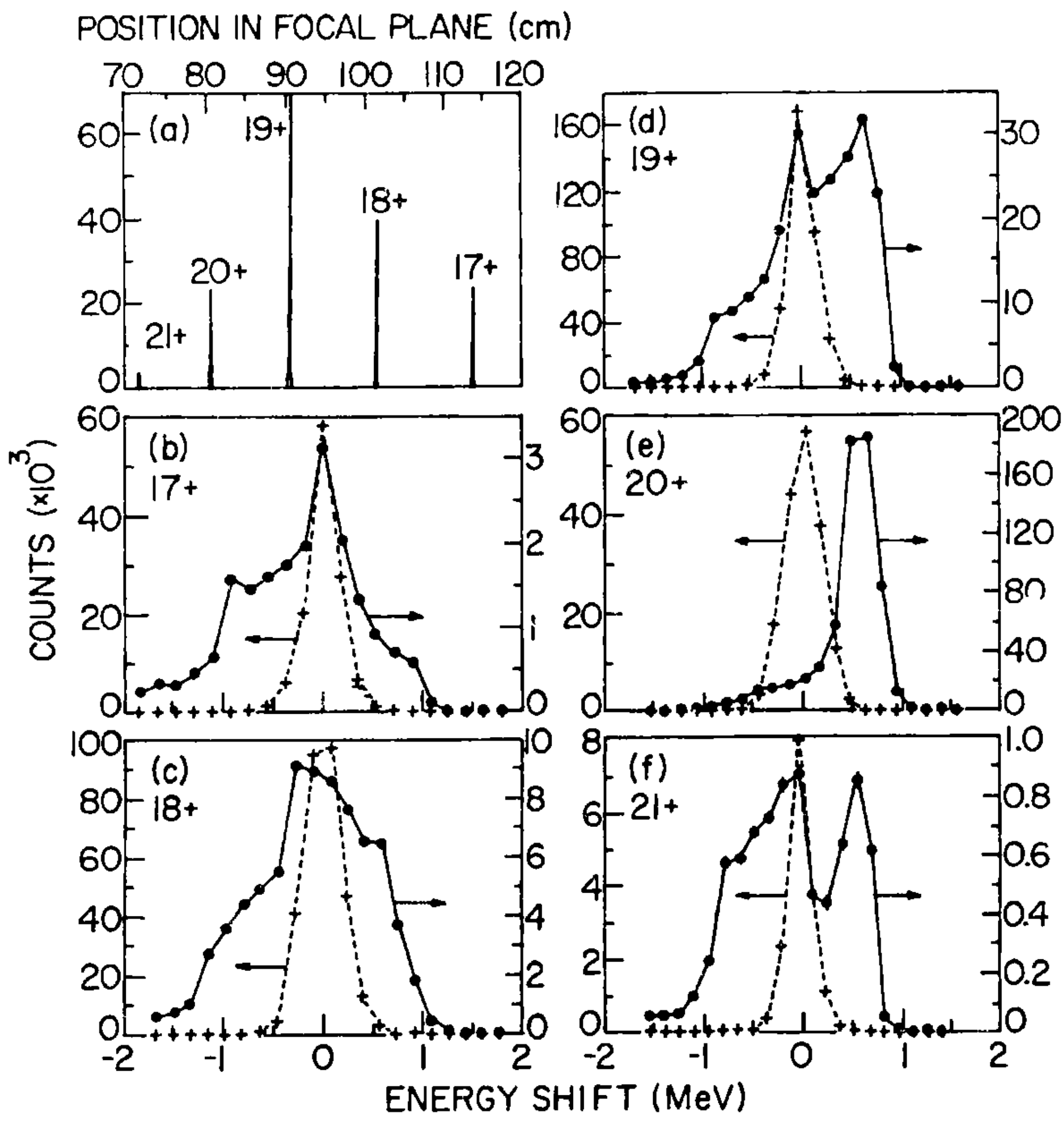

Fig. I-11. (a) Position spectrum measured with the focal-plane detector of the magnetic spectrograph for 293-MeV Ti^{20+} ions incident on a 1200 Å Au crystal in a "random" orientation. (b)-(f) Expanded views of the regions in the focal plane corresponding to the different charge states in (a) showing the energy distributions of the emergent ions. The solid curves resulted when the crystal was aligned to the <110> direction, while the dashed curves are the corresponding energy distributions for a random orientation. Note the different ordinates for the channeled and random distributions. The abscissas for (b)-(f) show the energyshifts relative to the centroid of the random distribution in each case, i.e., ions with positive energy shifts lose less energy than the average energy loss while negative energy shifts correspond to ions exhibiting enhanced energy losses. The frozen charge state (20+) is shown in (e).

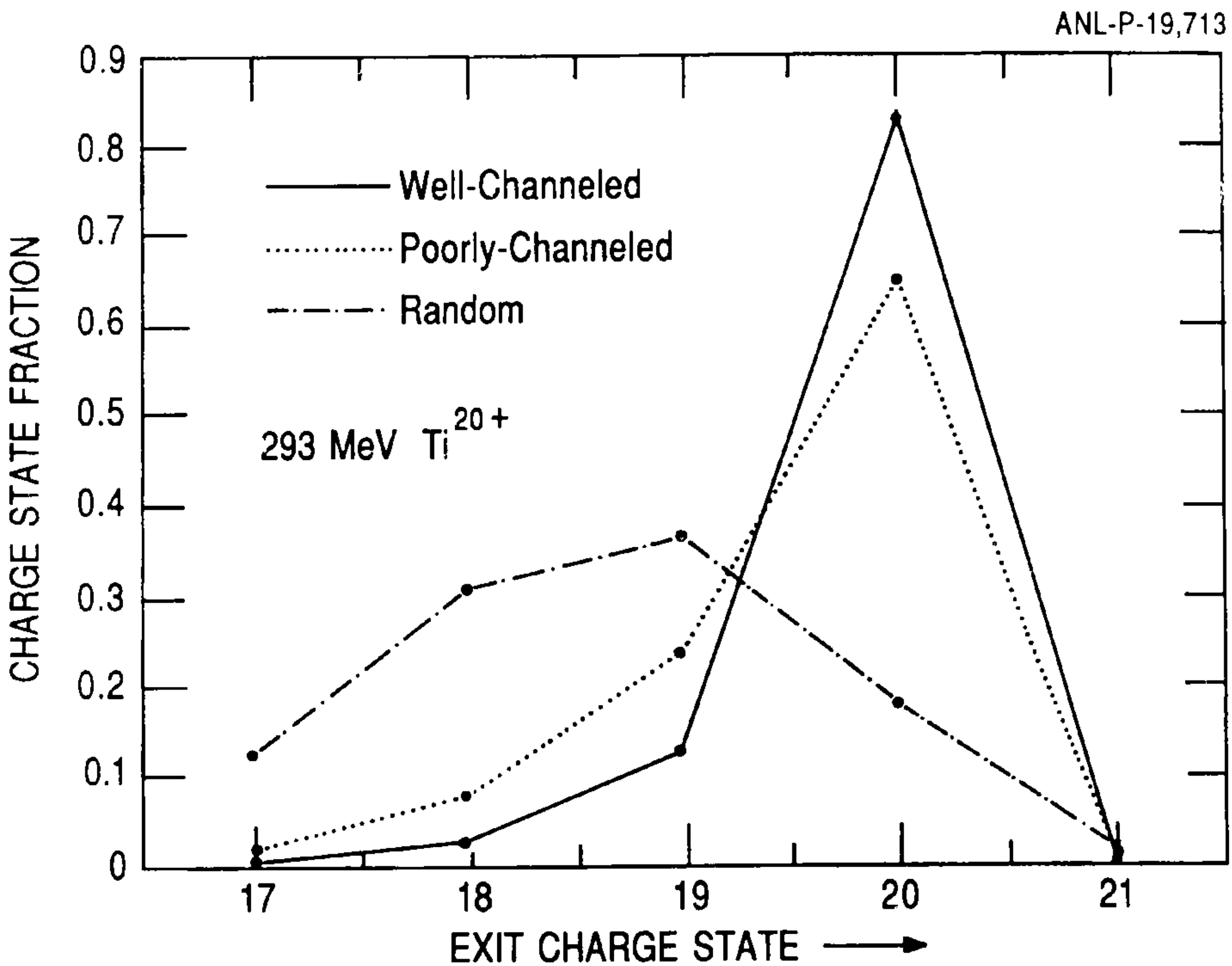

Fig. I-12. Exit charge-state fractions for 293-MeV Ti^{20+} ions incident on a 1200-Å Au crystal. The "well-channeled" and "poorly-channeled" fractions resulted when the <110> axis of the crystal was oriented along the beam direction. The random fractions were determined for an unaligned crystal orientation as described in the text. The well-channeled fractions are for ions with energy shifts ≥ 600 keV (see Fig. I-9), while the poorly-channeled fractions are for ions exhibiting shifts less than this value.

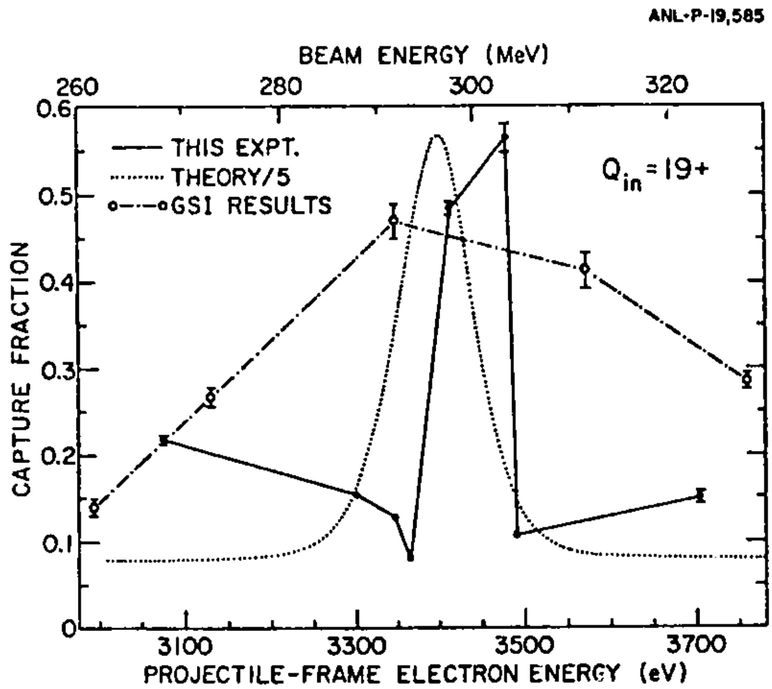

Fig. I-13. Fraction of hyperchanneled ions emerging as Ti^{18+} when Ti^{19+} ions are incident on a 1200-Å Au crystal aligned to the <110> direction (solid line and points). The solid line is drawn to guide the eye. Results for Ti^{19+} on H_2 are shown for comparison (dash-dotted line). The dotted line is a theoretical estimate using the Compton profile of H_2 divided by 5.

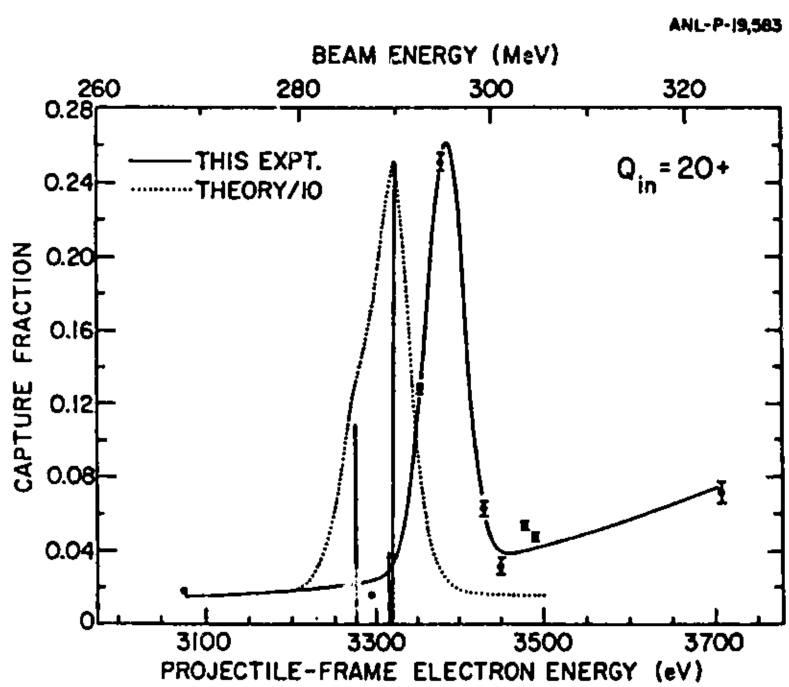

Fig. I-14. Same as Fig. I-11, but for hyperchannled ions emerging as Ti^{19+} when Ti^{20+} ions are incident. For the theoretical curve, the Compton profile of H_2 was divided by 10.

These results have caused several of the older low-resolution experiments to be reanalyzed and there now appears to be a systematic trend emerging. Previous measurements of Resonant Transfer and Excitation (RTE) carried out at Berkeley, Brookhaven, and GSI, all appear to exhibit a shift toward energies higher than theoretical predictions, with the deviation increasing with atomic number. This effect had never been observed before because of the broad widths of the observed resonances in those earlier poor resolution measurements.

These experiments have demonstrated that crystalline targets can provide a close approximation to an ideal electron gas in the study of ion-electron collision processes and to some extent alleviate the necessity of heavy-ion storage rings for many of these studies. It is therefore crucial to explain the puzzling energy shifts which have been observed so far. In order to investigate the Z dependence of these effects, we plan to extend these measurements to higher-Z systems (such as Fe and Ni ions) during the next year. While the work so far has concentrated on KLL transitions, we also hope to be able to extend these measurements to higher energies in order to investigate KLM and KLN transitions as well.

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

Studies relating to a condensed state in confined systems of cold ions have been continued. Such systems may be realized in ion traps or beams in storage rings. They are modelled in calculations on the Energy Research Crays using modified versions of the Molecular Dynamics program developed by the late A. Rahman. In the past year the simulations have been carried further and some preliminary experimental studies have been started at the Indiana University storage ring.

c.1. Properties of Ion Beams (J. P. Schiffer, R. Rafac, and O. Brewer)

In order to study the properties of beams in storage rings, a long calculation has been followed that incorporates somewhat realistic simulations of periodic focusing, of cooling, and of rotational shear with the objective to obtain visual images and possibly a video sequence. Many features are not necessarily clearly evident in simulations, unless one can follow them visually. A preliminary film has been prepared and improvements are now being attempted by transferring the files to the Ardent computer of the Argonne MCS Division.

c.2. Normal Modes (J. P. Schiffer)

Following the discovery that in simulations space-charge limited ionic beams exhibit strong resonant modes, such normal modes were also searched for in three-dimensionally confined systems, simulating ion traps. In isotropic confinement, a spherical ion cloud was found to undergo distinct shape oscillations, and quadrupole modes analogous to beta and gamma vibrations in nuclei are clearly evident. When the confinement becomes anisotropic, the normal mode frequencies of the spheroidal clouds change. Recently it was suggested by Dubin and O'Neil of San Diego, that such normal modes should also appear for higher multipolarities -- and they indeed are excited in the simulations. A systematic investigation of these frequencies as a function of the anisotropy of the spheroidal cloud has been started -- frequency dependences similar to those seen in nuclei are observed.

c.3. Shear in Particle Beams (J. P. Schiffer)

Earlier work on shear has been continued in a simulation in which a system is studied for a time that is equivalent to several hundred turns in a storage ring. This has required on the order of 50 hours of CRAY time and was run at low priority over a number of months. The particles seem to segregate into threads that slip with respect to each other, causing some interactions. The purpose of this calculation is to investigate whether the shear imposed by the rotation in a storage ring may cause inherently chaotic behavior in the system. The results are not yet conclusive.

c.4. Study of Isotropically Confined Simple Systems (R. Rafac and J. P. Schiffer)

The confinement of few ions in an isotropic field gives rise to well-defined geometric structures. These have now been characterized and the properties of these systems are better understood. Up to 12 particles remain on a spherical shell, but the 13th particle preferentially resides in the center of such a shell. When a second particle appears in the interior, this causes a slight anisotropy in the outer shell. The same geometric shapes that are seen for 1 - 12 ions appear in the interior of the larger systems, though the size of the configurations is somewhat larger.

c.5. Study of Anisotropically Confined Simple Systems (J. P. Schiffer, R. Rafac, and J. Hangst*)

The effect of changing to an anisotropic confining potential has been studied for the four-particle system which is a regular tetrahedron under isotropic confinement. Six distinct shapes have been identified as the strength of the confining force is changed in one direction compared to the other two. When the force is weak the configuration is linear. Then, with increasing force it first becomes a rhomboid, then a rhombus, a tetrahedron with three different length edges, a tetrahedron with two edge lengths (at isotropic confinement this goes through a regular teterahedron) and finally a planar square. The transition points between these shapes are being investigated more carefully and might perhaps become observable.

Graduate student, The University of Chicago, Chicago, IL c.6. Measurements at the IUCF Storage Ring (J. P. Schiffer, R. Pollock, T. Ellison,* D. Friesel,* and J. Hangst†)

Although the most favorable circumstance for observing ordering phenomena in cold ion beams is for heavy ions, some tests are being carried out at the IUCF Cooler, with stored protons. The tests were to understand the diagnostic system and eliminate as many perturbing effects as possible. Several features of a well-cooled beam were studied through the Schottky signals. Modifications to the IUCF cooler diagnostics are under way and should permit these studies to be carried out on a more quantitative level.

*Indiana University Cyclotron Facility, Bloomington, IN
†Graduate student, The University of Chicago, Chicago, IL

d. Search for Protons from the $^2H(^2H,p)^3H$ Reaction in an Electrolytic "Cold Fusion" Cell with Pd Electrodes (K. E. Rehm, W. Kutschera, and G. J. Perlow)

Several groups claimed to have observed excess heat and neutron production in electrolytic cells with Pd or Ti electrodes and heavy water as electrolyte. If the excess heat is caused by nuclear reactions various possibilities exist to measure the residual reaction products. At low energies the reaction rate for ^2H + ^2H collisions is dominated by the two reactions $^2H(^2H,n)^3He$ and $^2H(^2H,p)^3H$. While most experiments have concentrated on the neutron detection from the $^2H(^2H,n)^3He$ reaction we have studied the proton and triton production from the $^2H(^2H,p)^3H$ reaction. A small electrolytic cell (volume 12 cm^3) was mounted on a cylindrical proportional counter (PC). A thin Pd foil (thickness 25 μm) at the bottom of the electrolytic cell served both as cathode and as entrance window into the PC. As anode a 4.5-cm^2 strip of Pt was used in an electrolyte of 0.1 M ^{7}LiOD in D_2O (99.78%). The use of a PC instead of a Si surface-barrier detector allowed a much smaller low-energy cutoff (1.6 keV) and thus the possibility to search for low-energy electrons from the β decay of ^3H (β end point energy of 17 keV). Monte Carlo simulations showed that protons from the $^2H(^2H,p)^3H$ reactions should produce signals corresponding to energy losses of 200-1000 keV in the PC. The current densities in the electrolytic cell ranged from 10 mA/cm^2 to 600 mA/cm^2. The cell was operated over a period of 7 weeks using different Pd foils including a control experiment with H_2O as electrolyte. Before and after each run, background measurements with the electrolytic cell being switched off were performed. The electronic setup also allowed the investigation of the time dependence of the signals in the PC (proton bursts). The main background at low energy is caused by cosmic rays showing the well-known dependence on the barometric pressure. At higher energies the background is due to α particles from the decay of U and Th which are trace elements in the counter material.

From a comparison of the various runs with the cell being switched on or off an upper limit (2σ-limit) of 4×10^{-23} fusion events/deuteron pair/sec has been obtained which is too low by many orders of magnitude to explain the excess heat reported in some experiments as being caused by nuclear reactions. No indication of proton bursts has been found. The results have been published.

F. EQUIPMENT DEVELOPMENT AT THE ATLAS FACILITY

Considerable effort has been put in the development of the two new experimental stations in target area IV:

The Fragment Mass Analyzer (FMA) is scheduled to become operational in FY 1990. The support structure for the electric and magnetic elements has been installed and aligned. The construction of the ion-optical elements is near completion and the parts are scheduled to arrive within the next two months. The target chamber is presently being manufactured at the University of Notre Dame and will be completed in time for the first beam tests scheduled for the summer of 1990. The detectors for mass, Z and energy determination of the products in the focal-plane area have been built and tested with heavy-ion beams. Various other detectors (neutron detectors, tape-transport devices) are presently being developed by several outside user groups.

Preparations are well underway for the ATLAS positron-electron experiment APEX which is aimed at investigating the mysterious correlated positron-electron peaks observed in heavy-ion collisions at GSI. The new device which is capable of measuring the emission angles for positrons and electrons will have superior count-rate capability and will allow the measurement of the invariant mass of the decaying object.

The elements for transporting the beams from area III to area IV including a switching magnet have been installed and were tested recently with beams of the same magnetic rigidity as 6-MeV/u U^{50+}.

In addition to these two major items several smaller development projects were pursued during the last year. A new scattering chamber has been installed at the BGO facility which allows the mounting of a variety of particle detectors at forward angles for coincidence measurements with γ rays. Several experiments have already utilized this new capability.

Work is continuing on the Compton-suppressed Ge detectors for GAMMASPHERE. A first prototype detector has been tested and the performance of a new BGO shield has been evaluated. In a related investigation it was studied to what extent the resolution of Ge-detectors can be improved by correcting the pulse height measured for relatively slow signals.

First experiments using the method of a gas-filled spectrograph to measure fusion reactions at very forward angles proved to be very successful. It provides a new way to eliminate the high counting rate of beam-like particles in these types of reaction studies. Plans to use the same technique for Z-identification of very slow particles are presently being pursued.

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

The FMA is being constructed and instrumented by a collaboration of Argonne and University users of ATLAS. The collaboration consists of the following people:

Argonne National Laboratory:	C. Davids, B. Back, R. Betts, D. Kovar, B. Glagola, W. Kutschera, K. E. Rehm
Iowa State University:	J. Hill, F. Wohn
Louisiana State University:	E. Zganjar
University of Maryland:	W. Walters
Mississippi State University:	R. Piercey
University of Notre Dame:	J. Kolata, J. Vega
Vanderbilt University:	A. Ramayya, C. Maguire, A. Bavishi

The main ion-optical elements of the FMA are currently under construction by Bruker Analytische Messtechnik GmbH in Karlsruhe, FRG. The bending magnet, quadrupoles, power supplies, and the NMR will be shipped in the spring of 1990, with the electric dipoles to follow within a few months. The bending magnet has already been mapped, and it meets the magnetic field specifications.

The construction of the FMA support structure has been completed and is now installed in target area IV. A few pieces remain to be added, such as the angle and position encoders and a brake for the rotation motion. The utilities for area IV will be completed in time for the installation of the FMA elements when they arrive from Germany.

Construction has begun on a 15" diameter general-purpose sliding-seal scattering chamber for the FMA target position. The focal plane slit box is also nearing completion. All vacuum components for the FMA are currently in house, including cryopumps, ion pumps, turbomolecular pumps, valves, and special bellows and diagnostic crosses.

Figure I-15 (a) shows a schematic diagram of the FMA ion optics for one mass. (b) is an artist's conception of the assembled FMA.

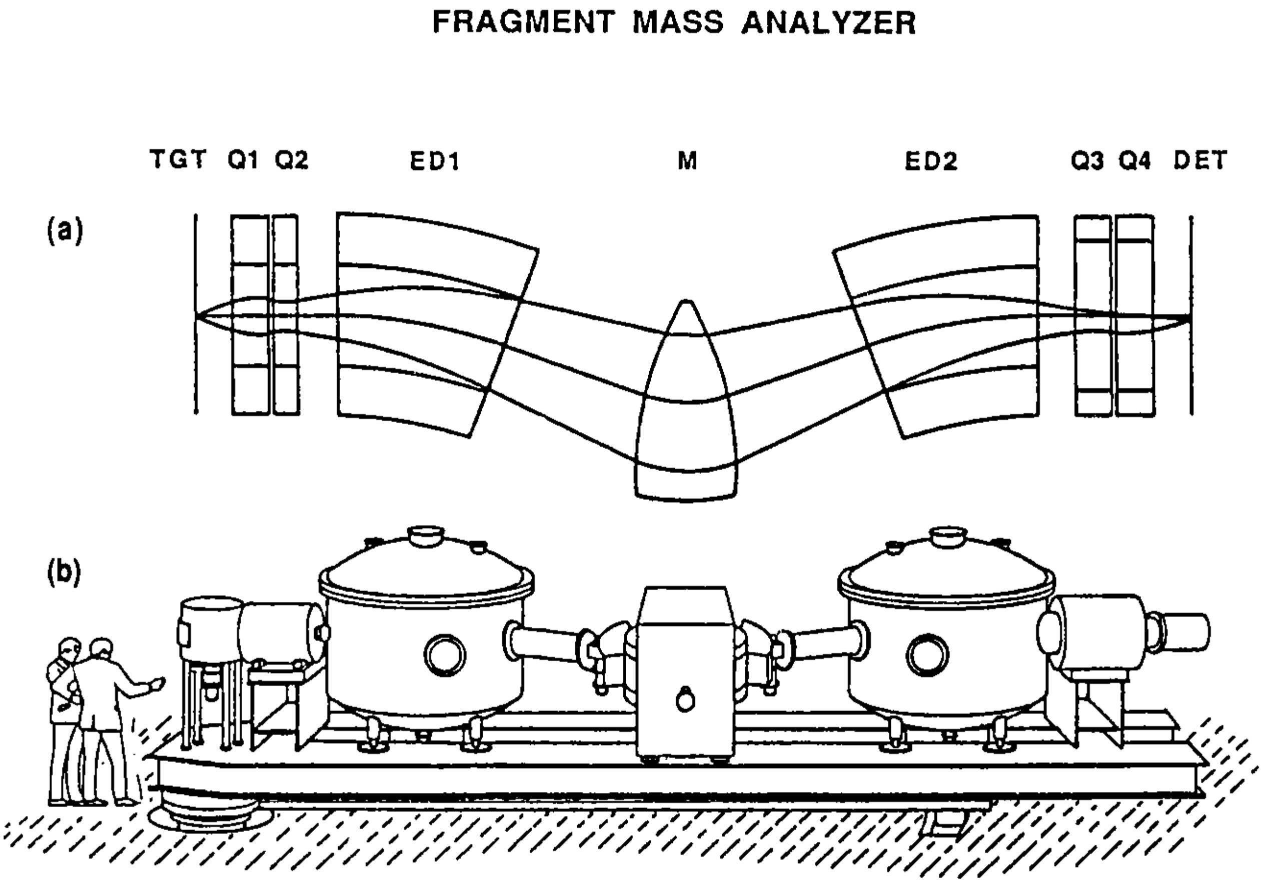

Fig. I-15. (a) Ion optics of the FMA showing the placement of the electric and magnetic elements. (b) Artist's conception of the assembled FMA.

A control and monitoring program for the FMA has been written, using a Macintosh computer. It currently allows the user to set the parameters of all the ion-optical elements, and displays these as well as the values of the support angle and position, and the temperatures and pressures in the high-voltage power supplies. It can also be used to automatically condition the high-voltage electrodes. New functions, such as control and monitoring of the scattering chamber parameters, can be easily added as needed. The computer is interfaced to the power supplies and other sensors via CAMAC.

A student from the Nuclear Structure Facility in New Delhi, India has arrived for a one-year stay to work on the FMA.

a.1. Development of Vacuum-Mounted High-Voltage Power Supplies for the FMA (C. Davids, J. Bogaty, B. Nardi, W. Kutschera, J. Magee, and T. Wu)

A new version of the 300-kV power supply has been developed. This supply utilizes a full-wave 30-stage Cockroft-Walton voltage multiplier and a commercial full-wave driver power supply, while the previous version used a half-wave multiplier and driver. The physical size has also been redesigned, in order to fit into the same readily available ceramic containers that were used with the Legnaro Recoil Mass Spectrometer electric dipoles. The new version has excellent performance, with a ripple of at 1.1×10^{-4} at 250 kV. Both positive and negative versions have been tested in vacuum to more than 250 kV (the design value for the FMA is 225 kV), and show a rapid conditioning behavior with the ceramic containers. A high-voltage conditioning algorithm has been developed for the FMA control and monitoring program. It uses the capabilities of the driver power supply to limit the current provided to the multiplier, thus allowing conditioning to proceed at the most efficient rate.

a.2. Development of a Sliding-Seal Scattering Chamber for the Fragment Mass Analyzer (B. B. Back, C. N. Davids, and J. Falout)

The design of the sliding-seal scattering chamber for the Fragment Mass Analyzer has been finalized and it is presently being fabricated at Notre Dame University. It is expected to be ready for installation in spring 1990. The chamber has a sliding seal for the beam entrance, since the chamber body will rotate with the Fragment Mass Analyzer. The sliding-seal assembly is presently being manufactured at Argonne.

a.3. Design and Fabrication of a Rotating Target Wheel

(B. B. Back, J. Done, H. Esbensen, and P. Wilt)

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 experiments with the Fragment Mass Analyzer, which can separate rare reaction products from the copious elastically scattered beam particles, particularly at forward angles. A computer program to calculate the temperature distribution of targets mounted at the periphery of a rotating target wheel was developed.

As a result of calculations using this program, 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. A target wheel adhering to these criteria has been designed and manufactured and is ready to be utilized in the sliding-seal scattering chamber for the Fragment Mass Analyzer.

In order to prevent the continuous beam from ATLAS (no macro structure) from striking the target frame, the beam is turned off using a fast beam sweeper, when a target frame passes through. The beam sweeper is controlled by a TTL signal generated from the output of a photo sensor, which views a reflective Al-strip placed directly on the target wheel. An electronic module, which generates the TTL signal for the beam sweeper, has been designed, and is presently being assembled and tested. This module also provides a digital readout of the target exposed to the beam, as well as a readout of the rotational frequency of the target wheel. This design allows for any rotation frequency up to the maximum, since the beam macro-pulsing is controlled by the target rotation and not vice versa.

a.4. Focal-Plane Detector for the Fragment Mass Analyzer
(D. G. Kovar, D. J. Henderson, and B. B. Back)

A low-pressure, position-sensitive Parallel-Plate Avalanche Counter (PPAC) for use at the focal plane of the Fragment Mass Analyzer has been designed, manufactured and tested. The active area of the detector is 5 x 15 cm^2, which is sufficient to completely cover the focal plane of the FMA. The detector was tested with ^{36}S ions elastically scattered from a Au foil. The incident beam was provided by the ATLAS facility. Position resolutions of $\Delta x = 1.4$ mm, $\Delta y = 1.6$ mm and a time resolution of $\Delta t = 570$ psec were obtained, even at high counting rates. The detection efficiency was above 86%. The performance characteristics are sufficient for satisfactory identification of reaction products reaching the FMA focal plane.

a.5. Bragg Curve Detector for the FMA Focal Plane (J. J. Kolata,* J. Vega,* B. B. Back, C. N. Davids, and D. J. Henderson)

This detector is being developed at Notre Dame University. It will be used at the FMA focal plane in conjunction with a thin multi-grid proportional counter that has been constructed and tested at ANL. The Bragg curve detector is patterned after one built at ANL, but is designed to fit the FMA focal plane. It has been tested with oxygen beams at Notre Dame and with a ^{58}Ni beam at ANL, and shows excellent charge resolution and an energy resolution of about 1.5%.

* University of Notre Dame, Notre Dame, IN

a.6. 16-Counter Neutron Detector Array for the FMA Target
(A. V. Ramayya,* C. F. Maguire,* A. Bavishi,* E. F. Zganjar,† R. Piercey,‡ and C. N. Davids)

The prototype detector for the 16-counter neutron array for the target area has been tested with neutrons, and shows high efficiency and very good neutron-γ discrimination properties. The remaining detectors are now being constructed, and will be sent to the vendor for reflective coating and filling with NE213 liquid scintillator. All photo-multipliers, bases, and shields are in house, and a support structure will be fabricated at ANL once the final configuration of the FMA target area is known.

*Vanderbilt University, Nashville, TN
†Louisiana State University, Baton Rouge, LA
‡Mississippi State University, State College, MS

a.7. Large-Area Scintillation Telescope (LAST) for the FMA Focal Plane
(R. Piercey,* A. V. Ramayya,† B. B. Back, and C. N. Davids)

The thin scintillation focal-plane detector (Mississippi State, Vanderbilt) will be used as a high-rate-event trigger at the FMA focal plane. It was tested with fission fragments and a Ni beam at ATLAS, and showed a time resolution of about 750 ps. Further work is expected to bring this down to less than 500 ns. It is hoped that the pulse-height signal from the detector can be used to obtain Z information about the ions.

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*Mississippi State University, State College, MS
†Vanderbilt University, Nashville, TN

a.8. Moving Tape Collector for the FMA Focal Plane
(J. C. Hill,* F. Wohn,* E. F. Zganjar,† and W. B. Walters‡)

The moving tape collector (Iowa State, Maryland, and LSU) is currently being designed, and construction will start in early 1990. It uses a long continuous tape, and will contain a deposition/parent counting port for short half-lived species and an optional daughter counting port. The ports allow beta, gamma, and conversion electron detectors to be mounted in close geometry. Provision is also being made for the measurement of angular correlations using four gamma-ray detectors. The entire apparatus will be mounted on a wheeled support structure to enable easy connection to the FMA focal plane.

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*Iowa State University, Ames, IA
†Louisiana State University, Baton Rouge, LA
‡University of Maryland, College Park, MD

a.9. Nuclear Spectroscopy/Nuclear Moments Facility for the FMA Focal Plane
(N. Koller,* G. Goldring,† and M. Haas†)

Plans for the nuclear spectroscopy/nuclear moments facility behind the focal plane are currently being made. A tilted-foil apparatus is under construction, and focussing studies have been made which show that a parallel beam can be extracted from the FMA which matches the geometry required by the tilted-foil array.

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*Rutgers University, New Brunswick, NJ
†Weizmann Institute, Rehovot, Israel

b. <u>The ATLAS Positron Experiment (APEX)</u>
(The APEX Collaboration - ANL, FSU, MSU, Princeton, Washington, Yale)

This experiment is aimed at the elucidation of the narrow peaks observed in the spectra of positrons produced in collisions of U+U and other similar heavy-ion systems. These mysterious peaks have been the subject of a long series of experiments at GSI - Darmstadt and many other related experiments elsewhere. The current status of the GSI investigations suggests that the narrow positron peaks originate from the two-body decay of some previously unknown neutral object(s), although results from other experiments place stringent constraints on the possible structure and lifetimes of such objects. The most pressing experimental question is the verification of the two-body decay hypothesis through a measurement of the angular and energy correlations between coincident positron-electron pairs produced in heavy-ion collisions. The APEX experiment is designed to carry out this measurement.

Briefly, the proposed apparatus consists of a large (4-m long, 1-m diameter) solenoid mounted transverse to the beam direction. A perspective drawing of the apparatus is shown in Fig. I-16. 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 hypothetical decaying object.

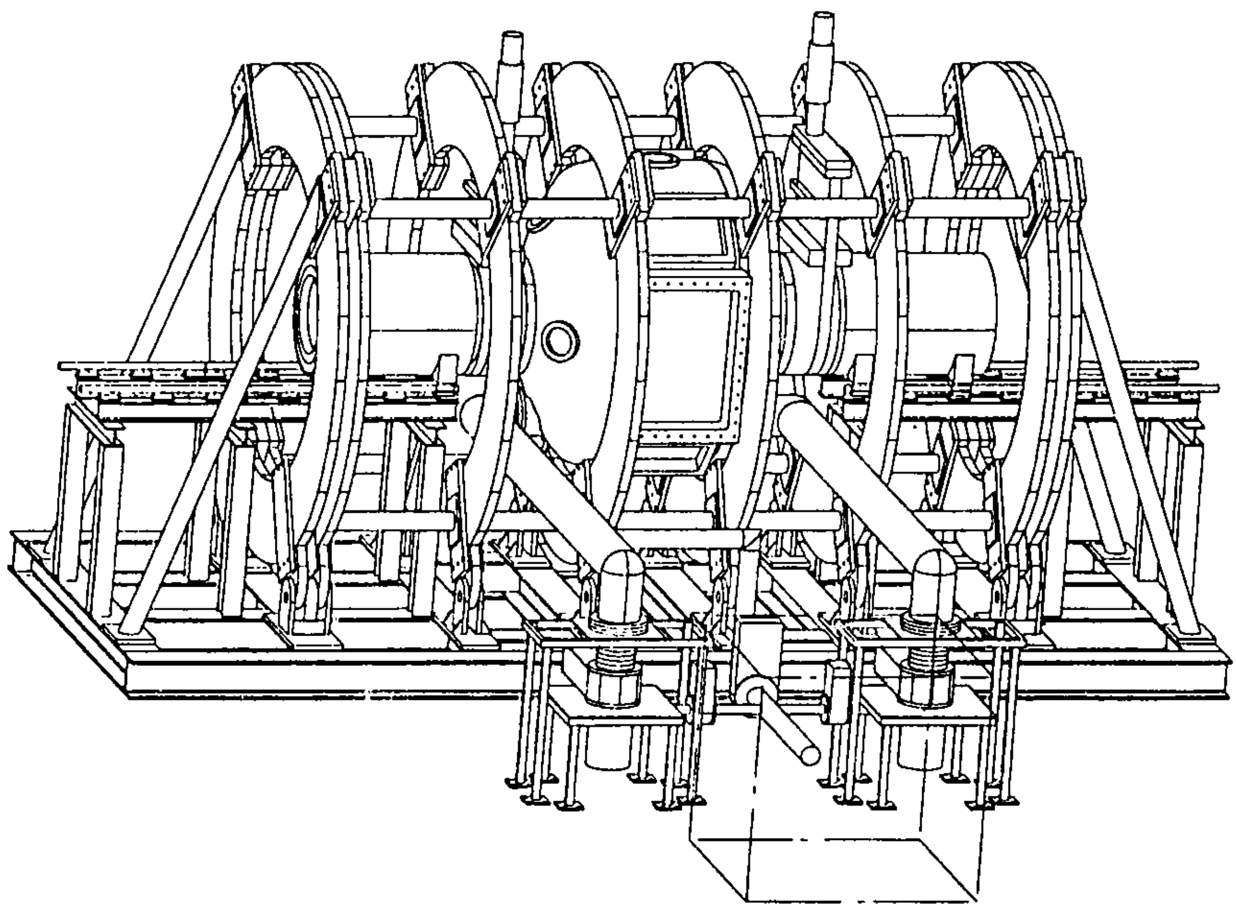

Fig. I-16. Perspective drawing of the APEX apparatus. Visible are the field coils, vacuum vessel with pumps, and the annhilation radiation detector arrays mounted on rails.

The APEX experiment is a collaborative effort between scientists from Argonne, Florida State, Michigan State, Princeton, University of Washington and Yale. The current members of the collaboration are:

Argonne:	I. Ahmad, R. Betts, R. Dunford, S. Freedman, B. Glagola, T. Happ, J. Last, J. Schiffer, J. Specht, P. Wilt, F. Wolfs, A. Wuosmaa
Florida State:	J. Fox
Michigan State:	S. Austin, E. Kashy, M. Maier, D. Mikolas, J. Winfield
Princeton:	F. Calaprice, A. Hallin
U. Washington:	T. Trainor
Yale:	P. Choudhury, J. Greenberg, K. Lister

In the past year the members of the APEX collaboration have been involved in design and development programs related to various aspects of the experiment. The final conceptual design of the apparatus was completed and detailed design, procurement, and construction is now under way. It is expected that the apparatus will be ready for operation in early 1991, at the same time that the heaviest beams become available from ATLAS.

The total budget for APEX is $2.35M, broken down as noted below:

APEX Budget

Item	Estimated Cost ($k)
Chamber, Solenoid and Power Supply	$ 374
Silicon Detector Array	266
Sodium Iodide Array	375
Heavy Ion Counter Array	58
Beam Line	137
Target Assembly	17
Silicon Electronics	336
Sodium Iodide Electronics	109
Heavy-Ion Counter Electronics	41
Trigger Hardware	204
Installation	90
Contingency and Inflation	343
	$ 2,350

The status of the individual components of APEX is given below.

b.1. Solenoid and Chamber Design
(A. Hallin* and F. Calaprice*)

The final coil arrangement for the APEX solenoid has been fixed, using eight coils from the MSU K=50 Cyclotron which have been made available to APEX. The support frame for these coils has been designed and is now being fabricated. The specification of the vacuum vessel, pumping system and associated hardware is now complete and detailed design is under way. The engineering design and fabrication is being carried out under contract with the Princeton Plasma Physics Laboratory. The completed coils, coil frame, and vacuum vessel will be installed at Argonne in Fall 1990.

*Princeton University, Princeton, NJ

b.2. Silicon Detector Array
(I. Ahmad, R. Betts, T. Happ, A. Wuosmaa, and T. Trainor*)

The APEX experiment contains two silicon detector arrays positioned on the axis of the solenoid. Each array will consist of 216 silicon detector elements each 3 x 0.5 cm^2 arranged on the surface of a hexagonal cylinder. These detectors provide information on the energy, time of flight and impact position of positrons and electrons which strike the array after spiralling down the solenoid. It has been specified that these detectors should be 1-mm thick and give <7-keV energy and <2-ns time resolution for few-hundred keV positrons and electrons. An initial set of prototype detectors was able to meet this specification only when cooled to near-liquid-nitrogen temperature, the difficulty arising primarily from the high reverse currents at room temperature in detectors made from the then-available material. A new set of prototype detectors, now incorporating a guard ring to shunt surface currents, have shown 6-keV energy and 1.2-ns time resolution at room temperature. The design of the full array with associated readout and cooling is now in progress. The final prototypes, now with the exact geometry required for the experiment, have been ordered and will be delivered in June 1990. Following evaluation of these detectors, the order for the bulk of the silicon detectors will be placed with delivery by the end of the year.

*University of Washington, Seattle, WA

b.3. Sodium Iodide Array
(J. Last, P. Choudhury,* J. Greenberg,* and K. Lister*)

Two barrel-shaped, position-sensitive NaI detectors will be used to detect the characteristic gamma radiation from positron annihilation in the silicon detectors. Each NaI detector will be divided in 24 trapezoidal elements, each 6-cm thick and 55-cm long. The azimuthal segmentation will allow us to create a clean trigger from back-to-back hits of 511-keV γ rays in the detector.

The detector elements are made position sensitive by evenly grinding the crystal surface, a technique that has recently become available. The result is an exponential attenuation of the scintillation light as it propagates through the crystal. By measuring the pulse heights from the two photomultipliers located on the end faces of each crystal the location of the scintillation event can be determined.

The work so far has been focussed on the testing and evaluation of prototype crystals of various sizes and cross sections. The basic setup consists of a collimated annihilation radiation source (^{22}Na) which is movable and allows the mapping of the crystal's surface. A second 2" x 2" NaI counter allows us to efficiently suppress the room background by requiring a coincidence between two 511-keV photons. The measurements show only slight variation of the energy and position resolution when the source is moved along the detector. Their typical values are 15% and 3.5-cm FWHM, respectively. The photopeak efficiency is approximately 60% and the time resolution was determined to be 3-ns FWHM.

Since the scintillation detector for APEX will be located in a homogeneous field of 300 gauss, normal 2" PMTs cannot be used. The only alternative is the R2490 PMT manufactured by Hamamatsu. The mesh dynode design of this tube allows its operation in a strong magnetic field parallel to its axis. Various tests of this tube have been conducted in fields up to 800 G. At 300 G the gain dropped only 2% and even at 800 G the loss is only 12%. The measured time resolution was less than 1-ns FWHM and independent of the magnetic field.

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*Yale University, New Haven, CT

The final design of the crystals and their support and shielding is now in progress. Procurement of the crystals and tubes will begin in early 1990 with delivery expected in the Fall.

b.4. Heavy-Ion Counters (D. Mikolas* and E. Kashy*)

The design of the APEX heavy-ion counter array is proceeding both at the level of the internal layout of the individual counters, and of the overall array structure itself. The general structure of the heavy-ion counters has been chosen, and the details of mechanical support and component layout remain. Several options are being developed for the array structure, with eight trapezoidal counters as faces of a truncated right octagonal pyramid as the most likely choice. The best option will be determined by a balance of cost and performance, based in part on the results of Monte Carlo calculations being carried out at NSCL.

The array will provide approximately 80% efficient coverage for U-like fragments at angles from 22 to 68 degrees and energies down to 0.5-MeV per nucleon.

Resolution in time of flight of 0.5-ns FWHM and in scattering angle of 0.15 degrees FWHM are expected. Scattering angle is determined by time difference between the two ends of a meander-delay-line cathode. The 15-degree segmentation of the array will provide information on the azimuthal scattering angle. NSCL has started work on a prototype heavy-ion counter element (one of eight elements which comprise the array). This element consists of three electrically separate low-pressure multiwire (LPMW) counters which share a common gas volume. The prototype will be ready for testing in early 1990 and tests of performance will take place within the month following the completion of the detector.

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*Michigan State University, East Lansing, MI

b.5. Electronics Development
(P. R. Wilt, F. L. H. Wolfs, and M. M. Maier*)

The electronics required to read out the APEX silicon detector array can be simplified when charge-integrating ADCs are used instead of the commonly used peak-sensing ADC's. We have explored the possibility of using either the LeCroy 2249W or the LeCroy 4300B charge-integrating ADC's without deteriorating the energy resolution (5 keV). We have shown that this can be accomplished by using the LeCroy 4300B in connection with a pulse stretcher. We are currently in the process of developing a prototype preamplifier that consists of a fast-timing pickoff, a slow-charge preamplifier, a pulse shaper and stretcher.

In parallel, we are currently evaluating the performance of the LeCroy 4290 TDC system. This system is well suited for APEX due to its high channel density and low cost per channel. The intrinsic TDC time resolution of 250 ps/channel is well below the time resolution obtained with the silicon detectors.

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*Michigan State University, East Lansing, MI

b.6. Monte Carlo Simulations (F. L. H. Wolfs)

The performance of APEX has been studied using Monte Carlo simulations carried out using the code EGS4, modified to include the transport of electrons and positrons in a magnetic field and to provide time-of-flight information. These studies were aimed at answering the following questions:

1. What is the background trigger rate produced by the large flux of primary γ rays and δ electrons?

2. What is the positron identification efficiency?

3. What is the invariant mass resolution, and what is the signal-to-background ratio in the invariant mass spectrum?

The primary background trigger rate arises as a result of an accidental coincidence between two detected heavy ions, two 511-keV γ rays in the appropriate segments of the scintillator, and an electron in the silicon detector array. The Monte Carlo simulations show that for a 10-pnA ^{238}U beam incident on a 300-μg/cm^2 ^{238}U target, we expect a background trigger rate of 3.4×10^{-2} s^{-1}. This is small compared with the true trigger rate of 9 - 18 s^{-1}. Another source of background which has been considered is the production of electrons and positrons by the primary γ rays interacting with the various materials in and around the solenoid. The estimated trigger rate due to this process is expected to be less than 4×10^{-2} s^{-1}.

Positrons are identified by detecting their characteristic annihilation radiation in a position-sensitive NaI array. From the measured detection position of each 511-keV γ ray in the NaI, the origin of the annihilation radiation on the surface of the detector array can be determined. This position information is crucial since in coincidence with each positron, on average 1-2 δ electrons are detected in other elements of the silicon array. Using the position information, we can determine which of the detector elements was hit by the positron.

The positron identification efficiency is defined as that fraction of positrons created at the center of the target, that produce a measured energy within 5 keV of the emission energy, and do not have a δ electron detected in one of the detector elements surrounding the silicon detector in which the positron was detected. The Monte Carlo simulations show that for 400-keV positrons the identification efficiency is 5.4% if no δ electrons are produced in coincidence with the positron. If the positrons are emitted in coincidence with 16 δ electrons (E_{e^-} > 20 keV), the positron identification efficiency is reduced to 4.8%.

The experiments carried out at GSI suggest that the electron-positron pairs might be produced via the decay of a neutral object with an invariant mass close to 1.8 MeV. A direct measurement of the invariant mass of this neutral object requires a measurement of the kinetic energy of both the electron and the positron, and their relative opening angle. For APEX the invariant mass resolution is expected to be 25 keV. This resolution is mainly determined by the resolution of the opening angle between the electron and the positron. The fraction of electron-positron pairs, produced by the decay of a 1.8-MeV neutral object, that contribute to the peak in the invariant mass spectrum is 3.3%.

b.7. Target Testing and Target Wheel Design
(A. Wuosmaa, R. Dunford, P. Pashigian, R. Betts, and J. Fox*)

In order to test the suitability of different targets for APEX, a series of measurements of the energy loss and straggling of ^{40}Ar ions passing through various U targets has been carried out. The experiments used an electrostatic analyzer to measure the energy of a beam of 2.5-MeV ^{40}Ar ions after passing through the target. (According to theory, 2.5-MeV ^{40}Ar should be equivalent in sputtering power to 5.9-MeV/u ^{238}U.) Targets of UF_4, U_3O_8 and U metal were tested. The UF_4 and U metal targets were found to be more uniform than the oxide targets. In addition, we were able to follow the deterioration of the targets during bombardment with intense beams with power dissipation similar to that expected in the APEX experiment. These experiments are continuing.

The design of the target wheel and its associated components is in progress. The wheel is an essential component in that it will allow the use of intense beams without destruction of the target which would occur due to heating if the target were stationary. Tests of motor operation in magnetic fields, vacuum feed-throughs for the target drive and schemes for indexing the target motion have been performed. The final design is currently being carried out.

Florida State University, Tallahassee, FL b.8. Beam Line Design (B. Glagola, W. Kutschera, and E. Kashy)

Optics calculations for the APEX beam line have been performed and a preliminary layout of the optical elements fixed. The effects of the external field of the solenoid on the beam transport have been considered and a scheme for compensating for these deflections chosen. The major components are being procured and the beam line installed at the same time as the solenoid and vacuum vessel.

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*Michigan State University, East Lansing, MI

c. Beam Line System to FMA and APEX
(W. Kutschera, B. Glagola, R. Kickert, and J. Specht)

The new target area IV will be equipped with two beam lines leading to the fragment mass analyzer (FMA) and the electron-positron spectrometer (APEX). The zero-degree extension from the second switching magnet in area III to a new switching magnet feeding these beam lines was completed. For a test of this section, a 293-MeV $^{58}Ni^{11+}$ beam was analyzed at the 33-degree (APEX) exit of the magnet requiring a field strength of 12.7 kilogauss. The magnetic rigidity of the Ni beam was equivalent to 6-MeV/amu $^{238}U^{50+}$ ions. The test showed that the switching magnet, which is a refurbished cyclotron-model magnet acquired from the Chemistry Division, can easily bend beams of the rigidity required for APEX experiments. The 10-degree beam line to the FMA is finished in its design, and the installation will be completed shortly. Four quadrupole lenses will allow the focusing of the beam into different shapes at the FMA target. A similar design is being considered for the APEX beam line.

d. Status of the Argonne-Notre Dame BGO Gamma-Ray Facility at ATLAS
(R. V. F. Janssens, M. P. Carpenter, E. F. Moore, I. Ahmad, J. Goral, T. L. Khoo, P. Wilt, K. B. Beard,* and U. Garg*)

The gamma-ray facility at ATLAS 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. During this past year the effort related to this facility has continued on several fronts:

- A second spare Ge detector was purchased, delivered and tested.

- Annealing because of neutron damage was performed twice on the four Ge detectors located at forward angles and once on 6 other detectors located at the other positions.

- The response of the CSGs to a set of mono-energetic γ rays with energies varying from 100 keV to 3 MeV were measured in the target position. These measurements are necessary for the accurate unfolding of the γ-ray spectra.

- The special target chamber designed for the measurement of g-factors was modified in order to facilitate the cooling of the target to LN2 temperatures.

- A variety of computer programs were developed in order to facilitate the set-up of the various parameters of the array (gains, constant fraction adjustments, high voltages...) and of the CSGs (gains of Ge detectors and check of Compton suppression).

- A new plunger device for recoil-distance lifetime measurements was designed and constructed at the University of Notre Dame where the device has also been undergoing first tests.

- Modifications to the LN_2 automatic filling system of the Ge detectors are underway. Special attention is being paid to the monitoring capabilities.

- Design studies on the coupling of the CSGs with the FMA have continued. It will be possible to place ten CSGs around a special target chamber in front of the FMA

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*University of Notre Dame, Notre Dame, IN

e. Scattering Chamber for the Argonne-Notre Dame γ-Ray Facility
(B. B. Back, S. J. Sanders,* J. Falout, J. T. Goral, and R. V. F. Janssens)

A specialized scattering chamber, which can be incorporated into the Argonne-Notre Dame γ-ray facility for particle-gamma coincidence experiments, has been constructed and installed. It allows for the installation of particle detectors forward of approximately 45°, both in-plane as well as out of the horizontal plane. The most recent phase of this project was the manufacturing of the back chamber, which supports the detectors and the target drive (which has been modified) and allows for a particle flight path of up to 1 meter. In addition, a new support for the chamber was designed and fabricated. This support allows for relatively easy installation and removal of the chamber, and minimizes the periods of down-time for the γ-ray facility.

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*University of Kansas, Lawrence, KS

f. Prototype Detectors and Other R & D Activities for GAMMASPHERE
(T. L. Khoo, I. Ahmad, M. Carpenter, P. Wilt, I. Bearden,* and R. V. F. Janssens)

A proposal was 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. Since GAMMASPHERE represents a national facility we are committed to participate in its construction. One of us (TLK) serves on the GAMMASPHERE Steering Committee which is charged by DOE with directing its construction and which has invested major effort in improving the design of GAMMASPHERE.

In preparation for the final design selection and construction of GAMMASPHERE, we at Argonne 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. With the completion of the test phase we shall present a plan to the Steering Committee offering to: (i) procure the Ge and BGO detectors, (ii) write the detailed specifications, (iii) define the testing procedure, and (iv) test a substantial fraction (half) of the detectors. It is expected that several other organizations (including university groups) will undertake to test the remaining detectors.

f.1. <u>Ge-Detector Design</u> (T. L. Khoo, I. Ahmad, and R. V. F. Janssens)

A prototype 70% n-type Ge detector has been ordered from Ortec. The first prototype detector constructed had microphonics problems and a second cryostat design is being considered. The prototype design incorporates many new innovations and represents a significant departure from present technology. It is, therefore, important to test if a such a detector can be successfully constructed. We have worked with the manufacturer, EG&G-Ortec, Richard Pehl (LBL) and members of the Steering Committee on the details of the design. The new design should also result in not only an improvement of higher rigidity but temperature. This is important since it has recently been recognized that a lower operating temperature makes a Ge detector more robust against neutron damage. Figure I-17 shows an outline of the Ge detector assembly.

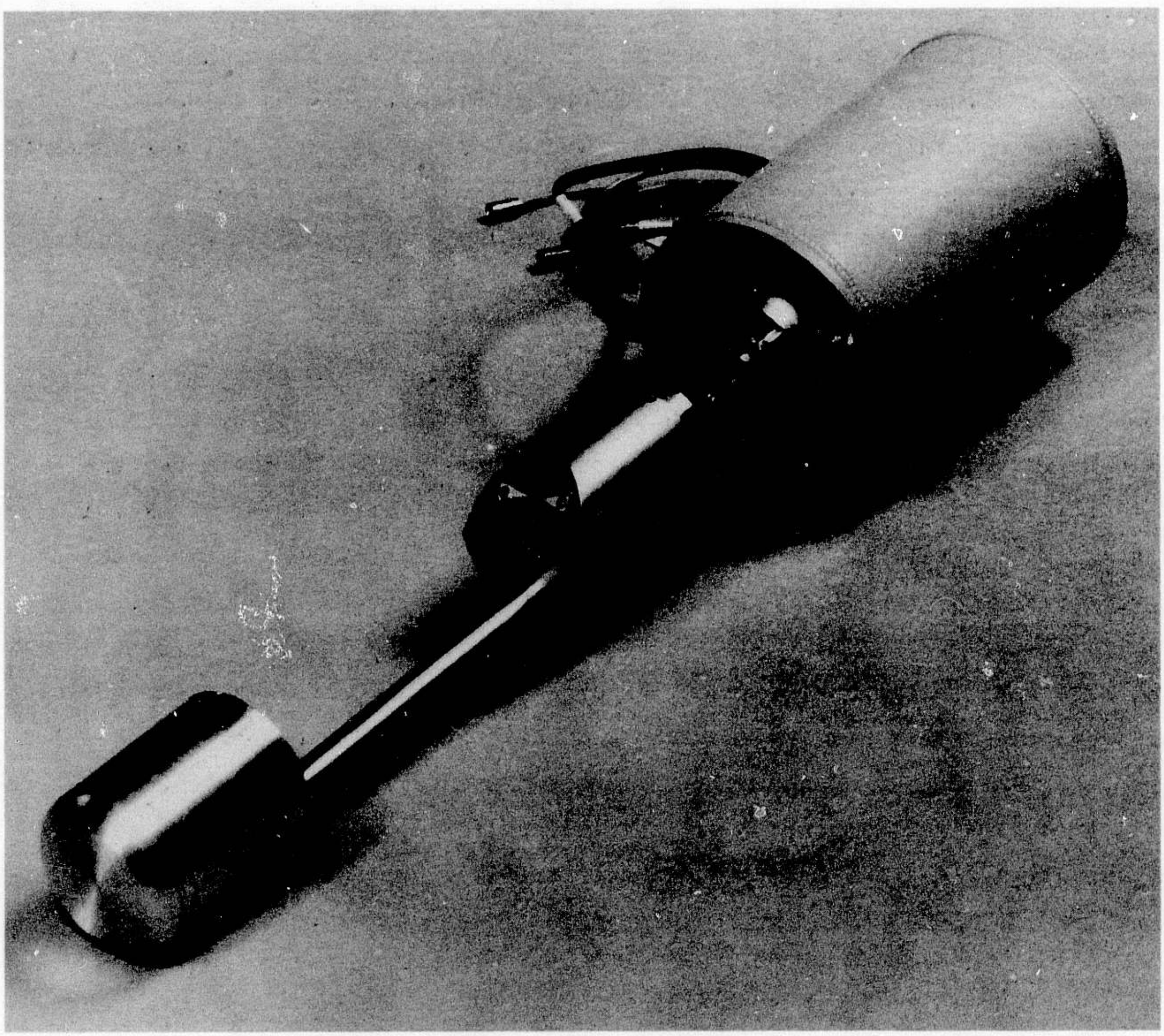

Fig. I-17. Prototype Ge detector for GAMMASPHERE.

f.2. BGO-Shield Design and Performance Tests (T. L. Khoo, I. Ahmad, R. V. F. Janssens, and I. Bearden*)

A complete BGO anti-Compton shield has been ordered from Harshaw. A back plug for vetoing forward-scattered γ's has been delivered and performs better than the specifications. The six BGO shield elements surrounding the Ge detector had some initial problems in light output uniformity and signal/noise ratio. However, after working with the vendor the problems have been solved. All 7 suppressor modules have been delivered and are being tested. Our measurements indicate that the units perform very well. Figure I-18 is a spectrum of the 60-keV ^{241}Am line, showing excellent peak/valley ratio, indicative of good signal/noise ratio.

It is already clear that the complicated shapes of the detectors do not compromise light collection and that they will allow for the low thresholds (~10-15 keV) necessary for optimal Compton suppression. Furthermore, the detectors are also suitable as spectroscopic detectors (FWHM at 661 keV is <20%) and have very good timing properties (2.6 - 3.4 ns FWHM for a ^{60}Co source).

We shall shortly evaluate the BGO detectors for their performance and efficacy as a Compton shield using Ge detectors we have at hand. The performance of a complete GAMMASPHERE module will be measured when the prototype Ge detector is delivered. The results of these activities will directly affect the selection of the final GAMMASPHERE Ge and BGO detector design. They will also provide a check on the Monte Carlo simulations performed at Oak Ridge.

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*Purdue University, West Lafayette, IN.

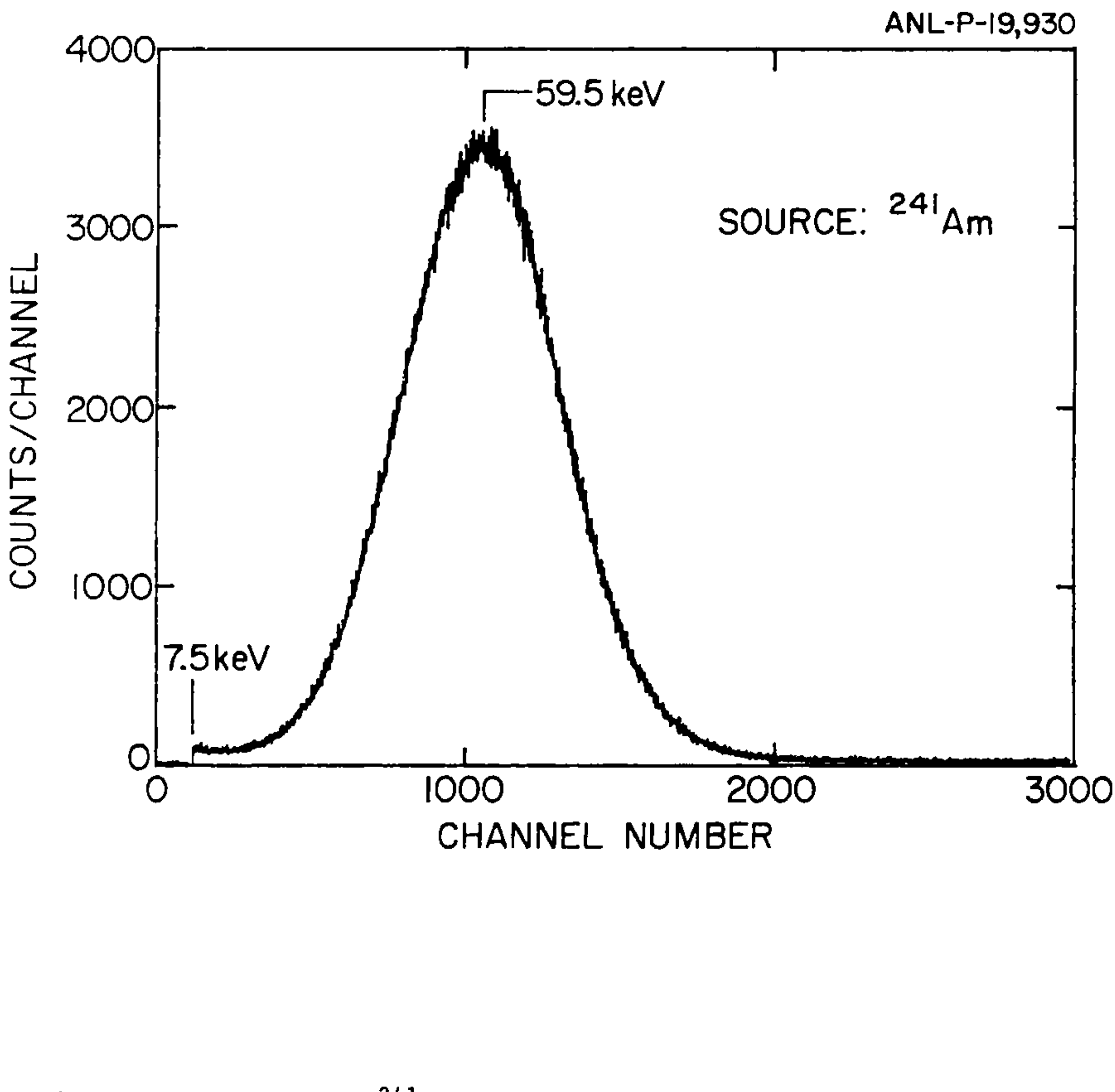

Fig. I-18. Spectrum of ^{241}Am for a side BGO suppressor detector. Excellent signal-to-noise ratio is measured.

f.3. Improving the Resolution of Ge Detectors (M. P. Carpenter, T. L. Khoo, F. L. H. Wolfs, R. V. F. Janssens, and I. Bearden*)

The energy resolution of a Ge detector is limited by the charge collection process when the shaping time of the amplifier is kept short (<=1 μs) in order to keep pulse pileup at an acceptable level. This is a consequence of the finite charge collection time associated with (i) interactions occurring in different parts of the detector (ballistic deficit) and (ii) charge trapping. Methods have been developed to correct for these defects using hardware (analog correction). We have performed the correction, using software with digitally-encoded information--the measured pulse amplitude and the cross-over time of the amplifier bipolar signal.[1] By applying a correction, based on a modification of the so-called Goulding-Landis method, the resolution with 1-μs shaping time improves from 2.8 to 2.2 keV. This effort is part of our contribution to the R&D effort for GAMMASPHERE.

We constructed two-dimensional histograms of the pulse amplitude and cross-over time. The trajectory in this two-dimensional histogram correlates the pulse-height deficit with the shift in the cross-over time and allows customized parametrization and correction of the pulse deficit for each individual detector. In addition it may be possible to isolate the separate branches associated with ballistic deficit, electron trapping, and hole trapping. This would permit correction for any one of the effects (with emphasis on the worst one), and perhaps permit correction of hole trapping which follows from neutron damage. (Present hardware correction techniques do not correct for neutron damage in n-type detectors.)

We have also implemented software correction of ballistic deficit using an alternative method developed by Hinshaw,[2] where the deficit is obtained from the difference in pulse amplitudes measured at two different shaping times. Our results indicate the following:

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*Purdue University, W. Lafayette, IN.
[1]F. S. Goulding and D. A. Landis, IEEE Trans. Nucl. Sci. 35, 119 (1988).
[2]S. M. Hinshaw and D. A. Landis, preprint (1989).

1. Both methods achieve impressive improvements in resolution using software correction--better than the hardware methods implemented to date. For example, the correction improves the resolution with 1 μs shaping from 2.8 to 2.2 keV (for 1333 keV) in a typical 25% detector. In the 80% detector, similar to those of GAMMASPHERE, with 2 μs shaping, the resolution improves from 2.61 to 2.17 keV (see Fig. I-19), even better than the FWHM at 2.25 keV measured at 6 μs shaping without correction.

2. For the so-called Goulding/Landis method, which corrects on the basis of the crossover time, Δt, the deficit ΔE is given by

$$\Delta E \sim \Delta t^n,$$

where n = 0.75-0.95. Previous implementaions of this method used theoretically derived values of n = 2 or 3.

3. We have demonstrated that it is possible to separate out events associated with neutron damage, and hence remove the large tail associated with these events by combining both the Hinshaw method and the modified Goulding/Landis methods. This was previously not thought to be possible for n-type detectors.

4. We conclude that ballistic deficit correction for GAMMASPHERE detectors should be done by software.

The cost for software correction is cheaper than that using present commercial hardware by about an order of magnitude. In addition, this correction may result in lower costs in Ge detectors by allowing the use of lower-quality Ge material which has more electron traps, but whose effects can be compensated for. Software correction also permits customized correction for each detector.

The results of our studies will also be applied to improve the Argonne-Notre Dame γ facility by allowing operation with 1-μs amplifier shaping time (instead of 3 μs), with a resulting threefold reduction in pile-up events, which now constitute ~30% of the total events.

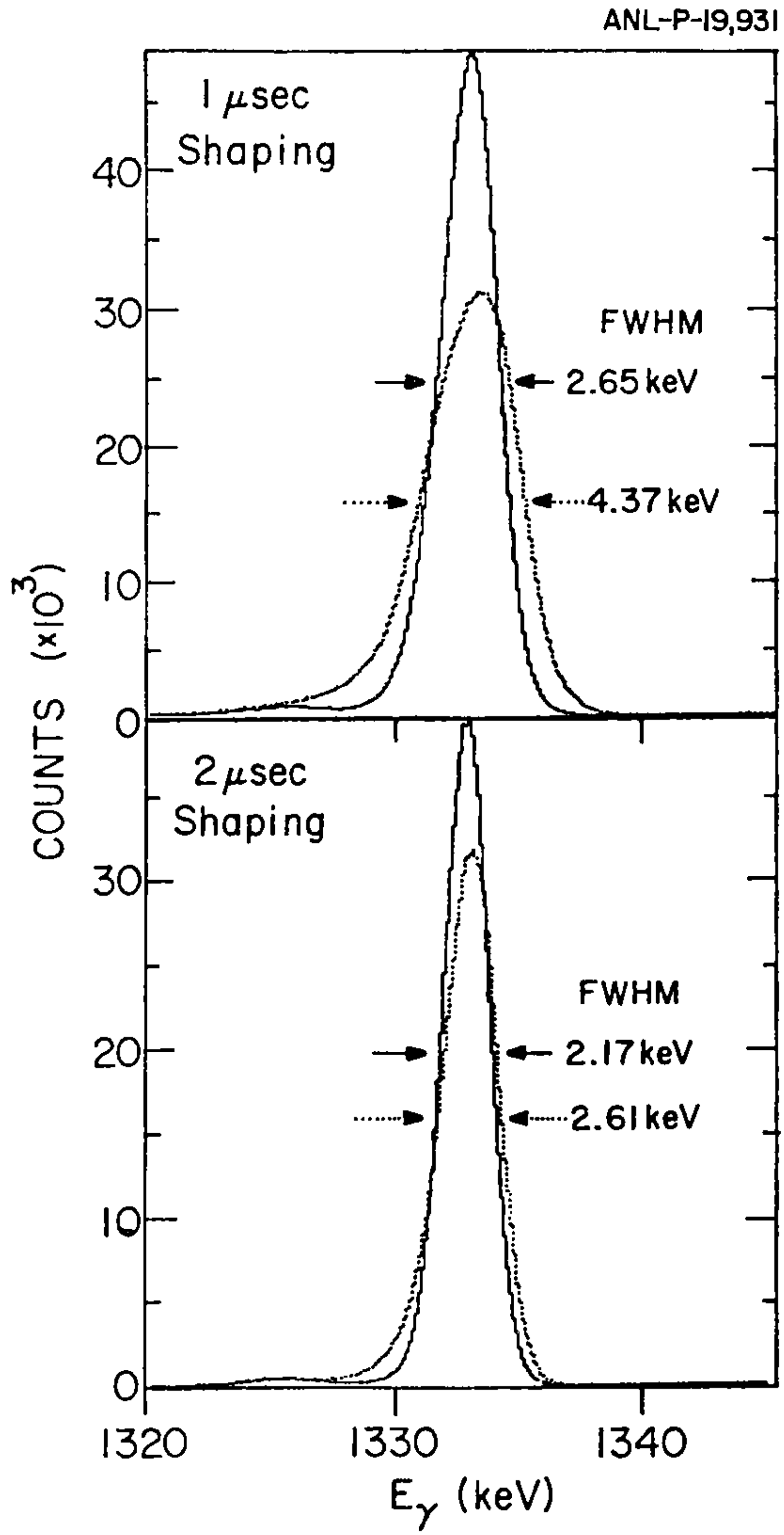

Fig. I-19. Spectra of 1333-keV ^{60}Co line obtained at 1 and 2 μs shaping with and without ballistic deficit correction (using the modified Goulding/Landis method in this case). An 80% n-type Ge detector on loan from Ortec was used for this measurement.

f.4. Trigger Logic and Pattern Recognition Electronics for GAMMASPHERE (P. Wilt, R. V. F. Janssens, T. L. Khoo, J. Haumann,* J. Hawkins,* and M. Meier†)

We have begun design of the first level trigger and pattern recognition electronics for GAMMASPHERE. We are also in the process of drawing detailed specifications for these units. The preliminary plans have been presented to the GAMMASPHERE Steering Committee and a group of electronics experts at two meetings on GAMMASPHERE electronics conducted at Argonne in March and May 1990. The group has endorsed the proposed design.

The first-level trigger logic is designed to make a decision in 500 ns based on: (a) number of Compton-suppressed Ge detectors, (b) total γ fold (hits), (c) total γ sum energy, and (d) external triggers. A noteworthy feature in the selecton of (a) is that the unit will be able to make sophisticated logic decisions, e.g. to implement a so-called electronic honeycomb option which greatly enhances the performance of GAMMASPHERE.

The pattern recognition unit accommodates 200 inputs and will recognize 4000 input preselected patterns as the condition for further processing of an event.

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*Electronics Division, ANL.
†Michigan State University, E. Lansing, MI.

g. The New Focal-Plane Detector for the Split-Pole Spectrograph
(K. E. Rehm, M. Nilsson, and F. Scarlassara)

The focal-plane detector for the spectrograph consisting of a position-sensitive Parallel-Plate Avalanche Counter (PPAC) and a Bragg-curve detector has proven to be very reliable and easy to operate for a large number of heavy-ion reactions. Recent experiments involving channelled heavy ions have shown the need for an improved position resolution. In its present configuration the position-sensing wire grid in the PPAC has a pitch of about 1.25 mm. Because of space limitations at the moment only every second wire is being connected to a tap of the integrated delay-line circuits resulting in a position resolution of 0.75 mm. We have now developed a modified printed circuit board which allows the readout of every single wire. The new board has been tested electronically and is presently being installed into the PPAC.

h. Computer Control of the Magnetic Field of the Split-Pole Spectrograph
(M. Nilsson and K. E. Rehm)

In order to automate the procedure for setting and controlling the magnetic field of the spectrograph, a computer program has been developed which allows the regulation of the power supply and the NMR readout of the split-pole spectrograph. The program uses commercial CAMAC hardware and CAMAC routines written for the data-acquisition system DAPHNE. The program allows the readout of the actual magnetic field, sets the field to a new value or ramps the field up or down at a specific speed and transfers the readout into the data header for data acquisition. The program has been used successfully in various experiments. It is also planned to incorporate a readout of the angle, the entrance aperture of the spectrograph, and the position of the focal-plane detector within the same program package.

i. The Study of Fusion Reactions with a Gas-Filled Magnetic Spectrograph
(K. E. Rehm, B. Glagola, T. Happ, and W. Kutschera)

Measurements of fusion reactions are generally quite time consuming due to the forward peaking of the fusion cross section and the high count rates of elastically-scattered particles at the forward angles. The use of a gas-filled spectrograph presents an elegant way to separate the lighter beam-like particles from the heavier fusion products, despite the fact that both have the same momentum.

We have started to investigate this method for the system $^{58}Ni + ^{64}Ni$ at the split-pole spectrograph. By measuring position and time of flight in the focal-plane detector, a clear separation of the evaporation residues from the elastically scattered particles was achieved. The use of the parallel-plate avalanche counter also allowed us to run at higher count rates than would have been possible with a position-sensitive ionization counter. We have studied the efficiency and the pressure dependence of the evaporation residue detection with N_2 gas in the range 0.5-2 Torr in the energy range between 200-300 MeV. The data are presently being analyzed.

In the future we plan to use two position-sensitive parallel-grid avalanche counters in order to measure fusion products and elastically-scattered particles separately, which will give us an automatic normalization to the Rutherford cross section.

j. Development of a Large-Area Detector for Multi-Particle Coincidence Experiments (R. R. Betts and A. Wuosmaa)

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 $\Delta E, E$ and position information. Prototype silicon detectors have been procured. Each detector is 5x5 cm with 16 strip electrodes on each side, one set of strips running in the x direction, the other in the y direction. These detectors thus provide simultaneous energy, timing, and x,y position information. Electronics suitable for use with these detectors is currently being designed using integrated-circuit multi-channel preamplifier circuits. A prototype circuit has shown < 40 keV resolution for 6-MeV α-particles. The first experiments with these detectors will be carried out this year.

k. Development of a Fast Beam Timing Detector
(B. D. Wilkins, D. H. Henderson, B. B. Back, L. M. Bollinger, P. K. Den Hartog, B. G. Glagola, D. G. Kovar, and R. C. Pardo)

The fast timing detector, based on the measurement of electrons emitted from the surface of a thin (10 μm diam.) tungsten wire struck by the beam and accelerated in a cylindrical electrical field, has been tested and found to function satisfactorily at low beam currents. A time resolution of $\lesssim$ 130 ps can be attributed to the detector system. In spite of the good performance of the wire detector, it has been decided not to proceed with its further development and deployment at the ATLAS facility, partly because of the difficulty in accepting a broad range of beam intensities and partly because of the successful development of an ultra-fast Faraday cup, which lends itself more readily to routine beam diagnostics. (See accelerator development section.)

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

The Physics Division operates a target development laboratory that produces very thin targets for experiments performed at the ATLAS and Dynamitron accelerators. Targets are made not only for the Physics Division but also for other divisions at the Laboratory and occasionally for other laboratories and universities.

In the past year, numerous targets were fabricated either self supporting or on various substrates, stretched films and "sandwiched" foils. Targets produced include Al, Au, Ag, ^{11}B, C, Ca, ^{156,160}Gd, ^{76}Ge, ^{6}Li, ^{24}Mg, ^{92,98}Mo, ^{208}Pb, ^{121}Sb, ^{144,154}Sm, ^{118,124}Sn, U, W, Y, ^{176}Yb and Zr. Targets prepared from compounds are ^{6,7}LiF, LiH, ThF_4,UF_4 and $^{238}U_3O_8$. In addition, films of Formvar and polypropylene were made.

Equipment used for thin-film deposition include the following:

1) A new 8-kw four-pocket electron beam source contained within an ultra-clean cryopumped system.

2) A second cryopumped system containing a focussed ion-beam sputter gun as well as capabilities for multiple resistive heating evaporations.

3) A diffusion-pumped system housing a vertical electron beam source for high-temperature reductions. In addition, this apparatus is routinely used for multiple resistive heating evaporations.

The equipment is maintained under high vacuum and each vessel contains a quartz-crystal film-thickness monitor with deposition-rate indicators. Also included are movable shutters, quartz-lamp substrate heaters and thermocouple temperature sensors. This enables complete process monitoring during target deposition.

Other auxiliary equipment used for target development includes a turbo-pumped glow discharge apparatus for plasma deposition, a small rolling mill, an α-particle thickness gauge, inert atmosphere glove box, laminar flow clean bench, a reduction furnace, and a variety of precision balances.

A target storage facility is in operation for maintaining, under high vacuum, those targets which can readily oxidize in air. This system utilizes a turbo pump and employs computer-controlled circuitry to help prevent the targets from exposure to the atmosphere during power interruptions. A second additional turbo-pumped chamber is now in routine use for target storage. This system uses electronically controlled valves for preserving the targets under high vacuum. In addition, there exists a bank of vacuum desiccators connected to a mechanically-pumped manifold for use by individual experimentalists.

The target laboratory maintains, for the Physics Division, a pool of stable isotopes as well as a sizeable collection of chemical compounds including a large complement of high-purity metals.

An IBM PC-XT computer system is in use within the lab. This system is capable of connecting with the Physics Division VAX as well as to the main Argonne computer facilities. A computer listing can be generated for inventory of all stable isotopes and chemicals maintained by the target development laboratory. Computer archives exist which contain information on previously requested targets that have been produced, dating back to 1978. A PCA system was recently purchased from Nucleus, Inc. consisting of an ADC card and associated software that allows the PC to act as a multi-channel analyzer. This acquisition, in conjunction with a recently built α-gauge setup, will provide an independent measure of target foil thickness. Energy-loss calculations for the foil material are carried out on the VAX.

A recently completed facility has been established dedicated to the production of low-level radioactive targets. An evaporator system obtained from the Chemistry Division has been restarted and tested. Some ThF_4 foils have already been produced. A second smaller evaporator system was constructed for close proximity evaporations so as to minimize contamination. The size of this system allows for operation within a hood. These evaporators, along with auxiliary equipment needed for target production, are housed in a separate lab dedicated to the use of radioactive materials.

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

Investigations are continuing on the construction of a rotating target-wheel evaporator system for the production of target foils to be used with the FMA.

Other areas of long-range development include acquisition of 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 by the technique of ablation, is an exciting new field of research which warrants further investigation.

m. Physics Division Computer Facilities
(T. H. Moog, D. R. Cyborski, and L. C. Welch)

The VAX-780 continues to serve as the hub for Division computing. It serves as a node on the Argonne DECnet, Bitnet, and HEPnet. It is expected that the VAX-780 will need to be replaced in the next year because of its high maintenance costs and relatively low performance compared to more modern machines. Total disk capacity has remained at about 2200 MBytes, which has been adequate.

The Division has purchased two VAXstation 3100 and two VAXstation 3200 (all with 600MB disks) in order to improve the computing resources of the Division. These have been combined with the VAX-780 to form a VAXcluster.

The terminal switch has been upgraded to handle more terminal lines as more computers are added. A terminal server has been added to provide terminal service over ethernet to VAX computers without a terminal line multiplexer. The terminal server also allows direct connections to other VAX computers at Argonne over the site-wide ethernet.

The weak interactions and medium-energy physics groups have purchased and installed four VAXstation 3100 and one VAXstation 3200 to create a VAXcluster using the medium-energy physics VAX-750 as a boot node. The Argonne members of BNL experiment E802 are using a Fermilab ACP computer system with 10 processors on the medium-energy physics VAX-750.

The ATLAS and Dynamitron VAX-750s continue to operate reliably. The Dynamitron VAX is routinely used for data acquisition and replay. The ATLAS VAX provides data acquisition for two simultaneous users at the ATLAS accelerator, as well as replay when CPU time and memory are available. The ATLAS VAX has been upgraded from 8MB to 14MB of memory in order to handle the greater number of histograms required for large, multi-detector experiments.

Two MicroVAX II computers are in the Division. Both have approximately 700MB of disk space and are equipped with DAPHNE data-acquisition hardware. One is located in the Area II data room and is used for replay and data acquisition. The other is used for data acquisition and analysis by the weak interactions group.

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

DAPHNE, the data-acquisition system developed for ATLAS, is routinely used for experiments at ATLAS and the Dynamitron. During the past year the microprocessor boards were upgraded to 512 kBytes in order to handle more complex user functions and a hardware module was modified so as to handle events with as many as 2048 parameters.

Even with these upgrades, several deficiencies still persist. Since the event handler does not have sufficient built-in intelligence, certain complex experiments cannot be handled with the existing hardware. Furthermore, the single-board computers have been discontinued by the manufacturer. We therefore plan to ugrade the acquisition hardware in the near future. Several possible configurations are presently being investigated.

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. Until 1989 the accelerator system consisted of a 9-MV tandem injector coupled to a linac with 42 superconducting accelerating structures. This system provides projectiles with energies >5 MeV per nucleon for ions with mass A < 100. In 1989, the overall capabilities of the system began to be enhanced by the addition of a second injector, an ECR ion source followed by a superconducting injector linac. The goal for this positive-ion injector, now partially installed and operational, is to extend the mass range up to uranium by early 1991. This program also includes some more general investigations of superconducting-linac technology.

A. OPERATION OF ATLAS

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

The layout of the ATLAS facility is shown in Fig. II-1. During FY 1989, the tandem electrostatic accelerator with its negative-ion source continued to be the injector of ATLAS for most of the running time. However, starting in March 1989, several exploratory runs were carried out with a prototype version of the new positive-ion injector (PII). The projectiles used were ^{3}He, ^{39}Ar, ^{40}Ar and ^{86}Kr, none of which are available from our negative-ion source. All of these runs were highly successful in the sense that the whole system (source, beam transport, bunching, and linac) worked as planned and indeed gave beams of excellent quality. The experiments with ^{3}He and ^{39}Ar gave useful research results. See Sec. D for additional information about the operating characteristics of the new injector.

The small size (3 MV) of the prototype injector linac limited the usefulness of PII to those beams in the lower third of the periodic table that are not available from the tandem. This limitation was removed to a significant extent in early 1990 when the injector linac was expanded to 7 MV. This enlarged version of PII was successfully tested in April 1990 by the acceleration of a $^{86}Kr^{15+}$ beam. Ten resonators housed in 2 large cryostats provided a total accelerating voltage of 7.0 MV, about 60% of the 12 MV expected from the final 18-resonator injector linac. The layout of PII relative to the rest of the ATLAS facility is shown in Fig. II-1.

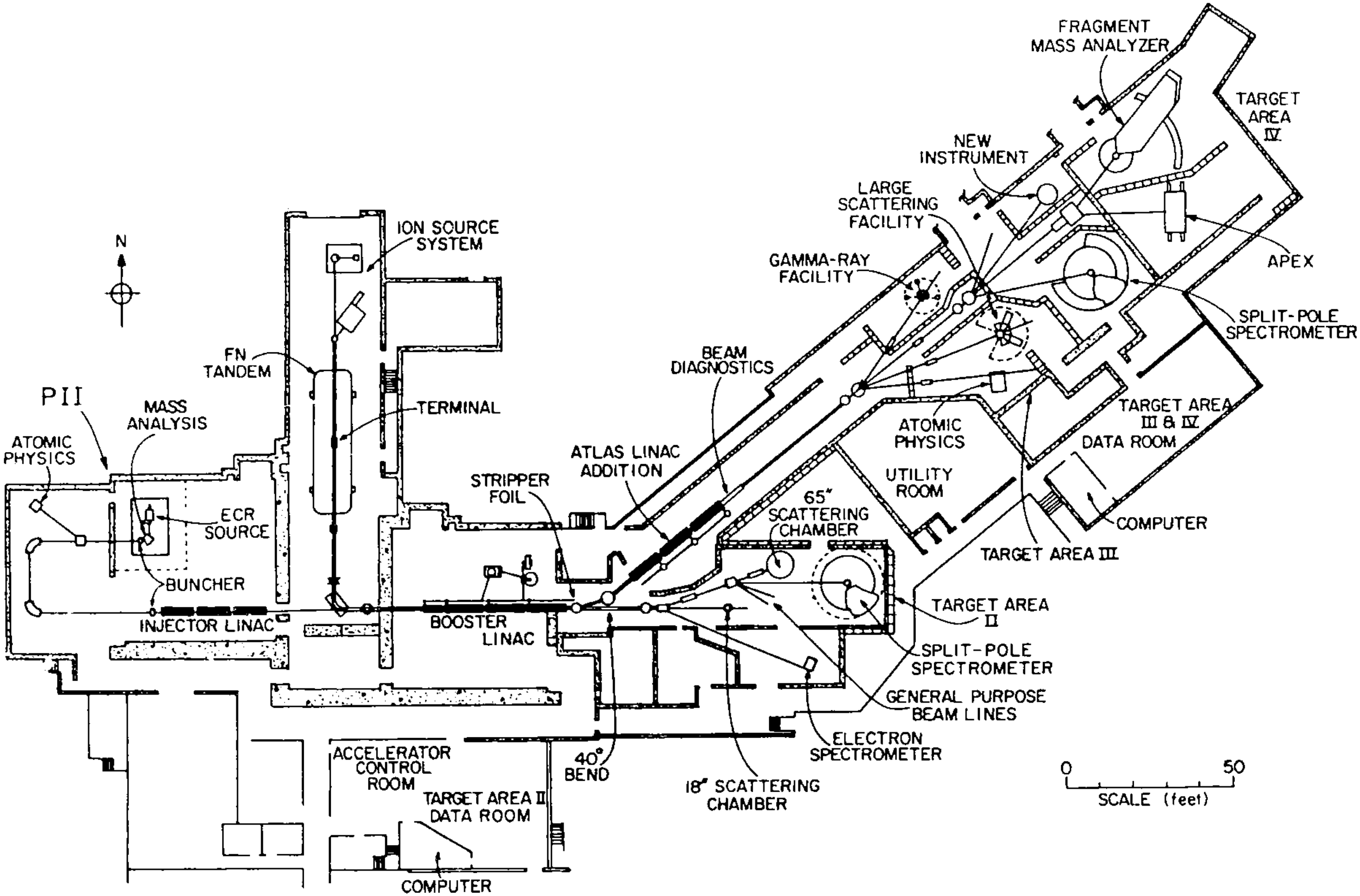

Fig. II-1. Layout of ATLAS. The system in use until May 1989 has consisted of the tandem injecting into the "booster" linac followed by the "ATLAS addition" linac. The new positive-ion injector is shown on the left side of the figure. All three cryostats of the new injector linac are shown, although only the two are now installed.

As a test of all aspects of the new injector system, the $^{86}Kr^{15+}$ beam from the ECR source was accelerated through ATLAS and used by Ernst Rehm and collaborators in a nuclear physics experiment at the Enge split-pole spectrograph. The systems $^{86}Kr+^{92}Mo$ and $^{86}Kr+^{54}Fe$ were studied at beam energies up to 400 MeV. The beam current on target was 4 pnA after passing through a 1 x 3-mm collimator system. The beam quality was excellent, with a phase-space area $\Delta E \bullet \Delta t$ of only 75 keV-ns (both ΔE and Δt are FWHM). This value is considerably smaller than any obtained previously for ions in the same mass range from the tandem injector. No beam contaminants of other isotopes or elements could be detected. During a 5-day run, the beam intensity was very stable and the ^{86}Kr consumption rate in the ECR source was about 1.2 mg/hr.

The 7-MV injector linac will be expanded to 8 MV later in 1990 by the addition of two more resonators, and this version of PII will be used regularly (but not exclusively) as the ATLAS injector until the final 12-MV injector goes into operation in early 1991.

Two somewhat different modes of operation of ATLAS injected by PII are feasible and will be used. In the mode employed to date, no stripper is used at the output of PII. The mass range that can be accepted for acceleration by the main ATLAS linac is determined by the requirement that the beam energy $E/A \gtrsim 2.1$ MeV/A at the entrance to the first so-called "high-β" resonator of the booster linac, which is ~7 MV downstream from the linac entrance. For the 8-MV injector, this implies that the charge-to-mass ratio accepted from the ion source must be $\gtrsim 0.155$. Projectiles up to the lighter tin isotopes satisfy this requirement.

In the second mode of acceleration, a stripper is used immediately after PII so that the increase in q/A provides additional acceleration in the input "low-β" section of the booster linac. This increase in energy before the ion arrives at the high-β section extends the mass limit to $A \approx 150$.

A stripper after PII introduces the complication that several charge states are accepted and accelerated through the booster section (see Fig. II-1) of the main ATLAS linac. The presence of several charge states is no drawback if the beam can be tuned, because the unwanted beam components can be removed by magnetic analysis at the 40° bend of the linac. The problem of tuning a beam with multiple charge states can be solved by tuning the system with a guide beam that has approximately the desired value of q/A and then adjusting linac parameters so that the ion of interest is accelerated with the same velocity profile as the guide beam. The validity of this simple idea has been demonstrated experimentally by using $^{16}O^{4}$ as the guide beam for $^{86}Kr^{21+}$. Note that a single guide beam can be used to tune many beams of interest, for example, all the isotopes of Kr. Also, PII can provide both the guide beam and the ion of interest.

The only limitation of the guide-beam technique is that is is not generally feasible to use a second stripper further downstream (for example, at the 40° bend), because the magnetic-rigidity spectrum would be too complex to permit reliable selection of the ion of interest. This limitation (and also the need for guide-beam tuning) will be removed in FY 1992 by installing a charge-state selector immediately after the post-PII stripper, if requested funds for the purpose are provided.

During the remainder of 1990 we intend to enlarge gradually the range of ion beams available to users. For relatively light ions ($A<80$), PII will be used only when the tandem injector is not suitable. For projectiles in the heavier mass range $80<A<150$, we are tentatively planning to concentrate initially on the isotopes of Kr, Mo, Sn, and Xe. PAC-approved experiments with beams of ^{79}Br, ^{83}Kr, and ^{92}Mo from the ECR source are scheduled.

Although operating experience with PII has been very successful in all basic respects, there have been some practical difficulties, of course. In particular, we continue to have trouble with breakdown of the isolation transformers used to provide power to equipment on the high-voltage platform of the ECR ion source. Hopefully, this problem will soon be a thing of the past, since new transformers have been ordered and are scheduled for delivery in early August. In the meantime and while PII as a whole is still in a somewhat developmental stage, the tandem is being used roughly half of the time as the source of ions for ATLAS.

During FY1989 ATLAS was usually operated on a schedule of 5-1/2 days of running time per week. In addition, the operation was sometimes extended through the weekend if needed to make up for the loss of scheduled time during the week. As a result of these extensions, most scheduled users got the amount of running time that the PAC had authorized. However, because of the need to shut down the normal operation of ATLAS while parts of the new positive-ion injector were installed and tested, the total running time available to users was less than it was in recent years. Some statistics concerning the operation of ATLAS are given in the table below, and the ion species accelerated by ATLAS during the past few years are summarized by Fig. II-2.

During FY 1990, additional 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. Also, the installation and testing of the second cryostat of the injector linac has required further reduction of the normal running schedule, so that the total running time available to users will be rather small again in 1990. However, starting in 1991, the beam time for users is expected to climb steadily toward an asymptotic value of 5000 hrs. in 1992. This expectation is contingent on funding at a level that will permit 7-day-per-week operation.

	FY1989	FY1990	FY1991	FY1992
Distribution of Machine Operation (hr)				
Research	3001	3500	4000	4500
Tuning	761	760	800	750
Machine Studies	563	500	600	600
Unschedule Maintenance	724	730	700	700
Scheduled Shut Down	3711	3270	2660	2234
Total (1 year)	8760	8760	8760	8784
Beam Use for Research (hr)				
Nuclear Physics	2558	3060	3550	4000
Atomic Physics	402	400	400	450
Other	41	40	50	50
Total	3001	3500	4000	4500
Number of Nuclear Experiments Receiving Beam	23	30	35	40
Number of Scientists Participating in Research	112	120	140	150
Outside Institutions Represented				
Universities (U.S.A.)	18	18	22	23
DOE National Laboratories	5	5	5	5
Other	4	5	7	7
Usage of Beam Tiem (%)				
In-House Staff	48	48	44	43
Universities (U.S.A.)	46	46	48	48
DOE National Laboratories	3	3	5	5
Other Institutions	3	3	5	5
Total	100	100	100	100

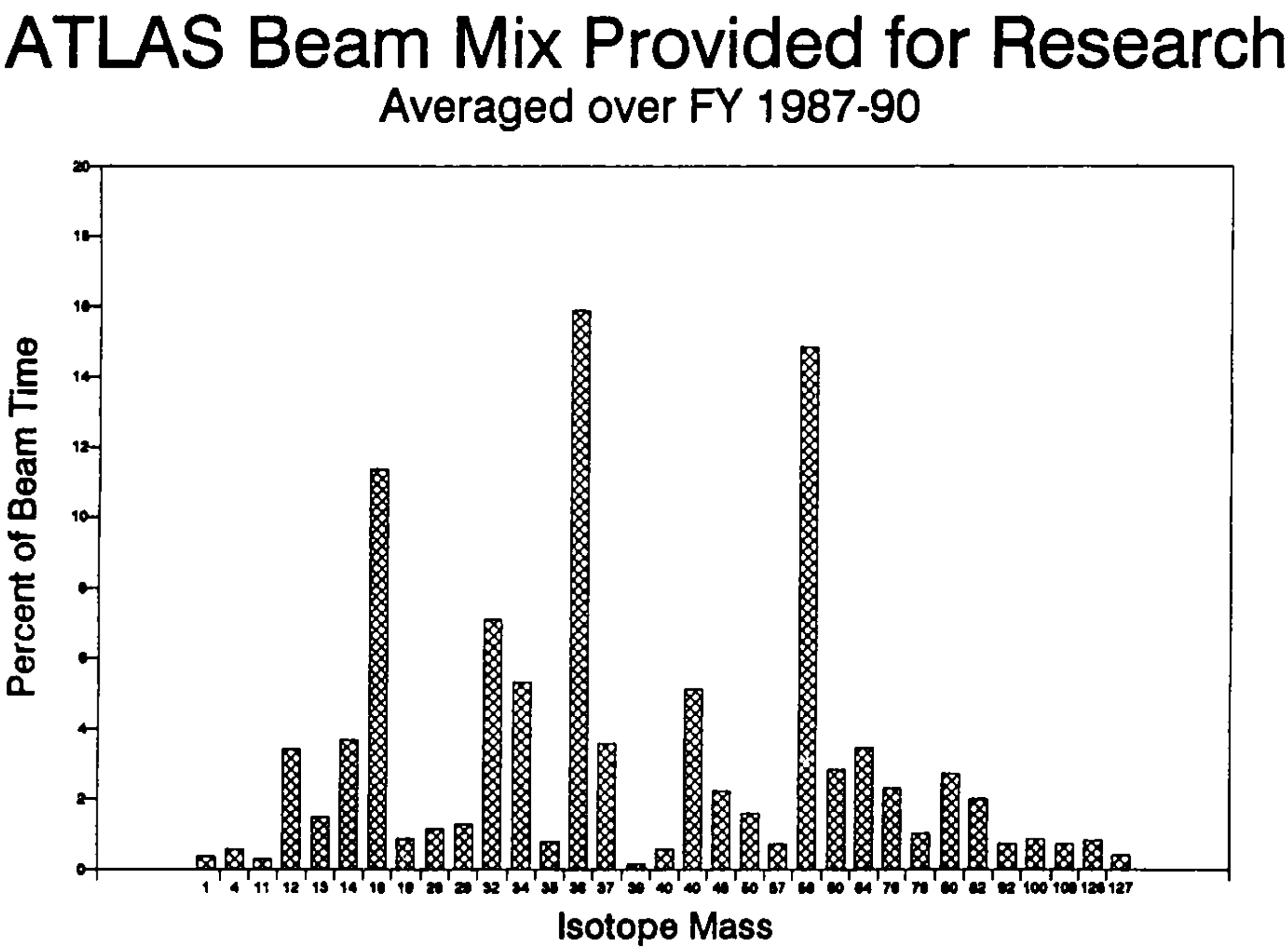

Fig. II-2. Frequency distribution of ions accelerated by ATLAS for research use during the past 3-1/2 years.

B. RECENT IMPROVEMENTS IN ATLAS

In addition to the major upgrade provided by installation of PII, various other parts of the ATLAS system are being improved to the extent that is feasible within the limits imposed by the available manpower, funding, and the operating schedule. There have been no significant changes in the tandem injector nor its ion source during this reporting period.

Refrigeration Capacity. The 100-watt helium refrigerator installed as a temporary source of cooling for PII was replaced by a 300-W unit in April 1989. Although the primary function of this unit is to cool PII, it can also provide about 40 watts of cooling for the main ATLAS linac. This additional cooling contributes significantly to the ease of operating and maintaining ATLAS.

The 300-W refrigerator is on indefinite loan from another program and could in principle be recalled. This unlikely event would create a crisis for the operation of ATLAS.

Phase Stability of Resonators. As reported last year, prior to 1989 the operation of ATLAS was plagued by occasional erratic changes in the phases of some resonators. It is now certain that this problem has been eliminated by replacing the original phase-distribution system by one of improved design. This improvement now makes it feasible to use a given beam tune many times, with the result that much less time was spent on tuning during the second half of 1989 and in 1990.

Now that we are confident that a calibrated phase setting will remain stable for a long time, a goal for the next year is to develop calculational methods to reduce further the tuning time.

Beam Bunching. The excellent stability provided by the new phase-distribution system (see above) has made it possible to detect and eliminate other imperfections. In particular, it revealed that an apparent wandering in the arrival time of beam pulses in the experimental area was not real but rather was instrumental in nature. Consequently, the original timing cables connecting the accelerator to the data room were recently replaced by phase-stable cables. This replacement eliminated the wandering and led to a significant improvement in the quality of time-of-flight spectra. ATLAS users who make use of fast timing are very pleased with this improvement.

Installation of Additional Rebuncher. The Enge split-pole spectrograph is so far from the main rebuncher on the ATLAS beam line that it has not been possible to produce at the spectrograph bunched pulses that are narrow enough for some measurements. To correct this problem, an additional rebuncher is being installed farther downstream, where it should be able to produce pulses ~100 ps wide at the spectrograph target. Its cryogenic installation has been completed but the new rebuncher has not yet been put into service.

Beam Lines into Area IV. The beam lines leading from Area III to Area IV have been installed and successfully tested. The large switch magnet on this line is a model magnet built in about 1968 in connection with an ANL proposal to build a large heavy-ion cyclotron (HIVEC). The new beam lines will be used to provide beams to two major new experimental systems: the FMA and APEX.

C. ASSISTANCE TO OUTSIDE USERS OF ATLAS

(Bruce G. Glagola)

The continuing strong interest in ATLAS (outside users were involved in over 80% of all experiments performed in 1989) makes it clear that the user-assistance program fills an essential function.

The outside user involvement continued to increase from that in 1988. 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 coordinating the operation of the technical support group; and (8) to provide an interface between the user and the technical support and ATLAS operation groups.

The Program Advisory Committee (PAC) for ATLAS (consisting of five members from other institutions and two from Argonne) continues to meet regularly during the year. PAC meetings were held on October 22, 1988, May 19, 1989, and November 18, 1989 to recommend experiments for running time at ATLAS. The present PAC members are Daniel Dietrich (Lawrence Livermore Laboratory), Robert Janssens (ANL), Peter Parker (Yale University), K. Ernst Rehm (ANL), Robert Vandenbosch (University of Washington), Victor Viola (Indiana University), and David Ward (Chalk River Nuclear Laboratories). On the average, the PAC is asked to review 25 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 ATLAS User Executive Committee organized a User Group meeting during the April, 1989 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. The 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 Astronomy Lab and M. L. Muga, Florida State University. For more details see section I.F.a., on the Fragment Mass Analyzer.

The prospect of uranium beams by early 1991 has brought about an ANL-FSU-MSU-Princeton-Yale-Washington collaboration to design and propose a positron experiment to investigate and resolve the question of "anomalous positron peaks" that have been seen at GSI. The APEX collaboration members are: S. Austin, E. Kashy, M. Maier, D. Mikolas, J. Winfield, Michigan State University; J. Greenberg, K. Lister, P. Chowdhury, Yale University; F. Calaprice, A. Hallin, Princeton University; J. Fox, Florida State University; and T. Trainor, University of Washington. For more details see section I.F.b., on the APEX project.

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 1989 are listed below. The spokesperson for each experiment is given in square brackets after the title. The names in parentheses are Argonne collaborators.

(1) Test of a New Type of Scintillator Detector for Charged Particles [Maguire]
C. Maguire, J. Shea, D. Oliver, Vanderbilt University; (B. G. Glagola)

(2) Superdeformation Near A=190: Lifetime Measurements [Janssens]
Z. Grabowski, P. Benet, Purdue University; U. Garg, K. Beard, D. Ye, University of Notre Dame; M. Drigert, Idaho National Engineering Laboratory; (R. V. F. Janssens, I. Ahmad, F. Wolfs, E. F. Moore, T. L. Khoo)

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

(4) Resonant Transfer and Excitation of Channeled Ions [Kanter]
J. Tanis, E. Bernstein, S. Ferguson, K. Lifrieri, University of Western Michigan; D. Schneider, M. Clark, Lawrence Livermore National Laboratory; K. Berkner, Lawrence Berkeley Laboratory; (E. Kanter, A. Belkacem, E. Rehm)

(5) Search for Superdeformed States in ^{144}Gd [Janssens]
M. Drigert, Idaho National Engineering Laboratory; U. Garg, D. Ye, K. Beard, University of Notre Dame; (R. V. F. Janssens, E. F. Moore, T. L. Khoo, I. Ahmad, R. Chasman, F. Wolfs)

(6) Complete and Incomplete Fusion in ^{40}Ca+^{12}C and ^{28}Si+^{24}Mg [Vineyard]
M. Vineyard, G. Gilfoyle, R. Trotter, S. Sigworth, University of Richmond; F. Prosser, University of Kansas; C. Maguire, Vanderbilt University; (D. Kovar, B. Glagola, D. Henderson, J. Mateja)

(7) Slope Anomalies in ^{58}Ni+Sm One- and Two-Neutron Transfer Reactions [Betts]
J. Lilley, Daresbury Laboratories; S. Sanders, University of Kansas, (R. Betts, E. F. Moore, K. E. Rehm)

(8) Lifetime of the 2^1S_0 State of Helium-Like Br^{33+} [Dunford]
D. Church, Texas A&M University; M. Hass, University of Rochester; (R. Dunford, C. Liu)

(9) Test of a Phoswich Detector and an Ionization Chamber [Viola]
V. Viola, K. Kwiatkowski, J. Wile, S. Yennello, D. Fields, Indiana University; (B. Glagola, D. Henderson)

(10) Neutron-Charged-Particle Coincidences to Study Heavy-Ion Interactions [DeYoung]
P. DeYoung, C. Copey, J. Sarafa, Hope College; G. Gilfoyle, S. Sigworth, University of Richmond; J. Kolata, R. Kryger, S. Dixit, J. Vega, R. Tighe, W. Chung, University of Notre Dame; (D. Kovar)

(11) Subbarrier Fission Angular Distributions [Ikezoe]
H. Ikezoe, JAERI, Japan; (B. Back, B. Glagola, T. Happ, D. Henderson)

(12) Light Charged Particles as Probes of Hot Composite Nuclei of $A \simeq 150$ [Kaplan]
M. Kaplan, E. Vardaci, W. Parker, P. Karol, D. Moses, Carnegie-Mellon University; P. DeYoung, C. Copey, J. Sarafa, Hope College; G. Gilfoyle, S. Sigworth, University of Richmond; (K. E. Rehm)

(13) Superdeformation Near A=190? [Janssens]
K. Beard, D. Ye, University of Notre Dame; P. Benet, Purdue University; M. Drigert, Idaho National Engineering Laboratory; (R. V. F. Janssens, T. L. Khoo, E. F. Moore, F. Wolfs, I. Ahmad, M. Carpenter, P. Fernandez)

(14) Gamma-Ray Width of the $^{14}O^*$ (5.17-MeV) State [Parker]
P. Parker, P. Magnus, M. Smith, K. Hahn, R. Curley, Yale University; S. Sanders, University of Kansas; T. F. Wang, Lawrence Livermore National Laboratory; (K. E. Rehm, C. Davids, P. Fernandez)

(15) Measurement of the Intrinsic Quadrupole Moment of the Superdeformed Band in ^{151}Dy [Moore]
K. Beard, D. Ye, University of Notre Dame; P. Benet, Purdue University; M. Drigert, Idaho National Engineering Laboratory; (R. V. F. Janssens, E. F. Moore, T. L. Khoo, F. Wolfs, I. Ahmad, M. Carpenter, P. Fernandez)

(16) Excitation Function for the Population of the Superdeformed Band in ^{191}Hg [Janssens]
D. Ye, K. Beard, U. Garg, University of Notre Dame; P. Benet, Purdue University; M. Drigert, Idaho National Engineering Laboratory; J. Cizewski, Rutgers University; (R. V. F. Janssens, E. F. Moore, R. Chasman, I. Ahmad, M. Carpenter, T. L. Khoo, F. Wolfs)

(17) Study of the Decay Out of the Superdeformed Band in ^{191}Hg [Ye]
D. Ye, K. Beard, U. Garg, University of Notre Dame; P. Benet, Purdue University; M. Drigert, Idaho National Engineering Laboratory; J. Cizewski, Rutgers University; (R. V. F. Janssens, E. F. Moore, R. Chasman, I. Ahmad, M. Carpenter, T. L. Khoo, F. Wolfs)

(18) Dynamical Screening of Channeled Ions [Kanter]
J. Tanis, E. Bernstein, S. Ferguson, University of Western Michigan; D. Schneider, M. Clark, Lawrence Livermore National Laboratory; K. Berkner, Lawrence Berkeley Laboratory; W. Graham, Queens Ulster; (E. Kanter, K. E. Rehm, A. Belkacem)

(19) Hyperfine Quenching of Forbidden Decays in Helium-Like Fe^{24+} [Dunford]
D. Church, Texas A&M University; (R. Dunford, C. Liu, N. Mansour, R. Vondrasek, J. Last)

(20) Decay of the Superdeformed Band in ^{152}Dy: Search for a Time Delay and the Decay Pathways [Khoo]
M. Drigert, Idaho National Engineering Laboratory; D. Ye, K. Beard, University of Notre Dame; P. Benet, Purdue University; (E. F. Moore, M. Carpenter, P. Fernandez, R. V. F. Janssens, T. L. Khoo, I. Ahmad)

(21) Search for Superdeformed Structures in the Odd-Odd Nucleus ^{190}Au [Carpenter]
L. L. Riedinger, University of Tennessee; P. Benet, Purdue University; U. Garg, University of Notre Dame; (M. Carpenter, P. Fernandez, T. Happ, E. F. Moore, I. Ahmad, F. Wolfs, T. L. Khoo, R. V. F. Janssens)

(22) Magnetic Moments of High Spin Levels [Hass]
M. Hass, University of Rochester; N. Koller, Rutgers University; P. Benet, Purdue University; K. Beard, University of Notre Dame; (M. Carpenter, F. Wolfs, T. L. Khoo, I. Ahmad, E. F. Moore, P. Wilt, P. Fernandez, R. V. F. Janssens)

(23) Search for Production of Long-Lived Spontaneous Fission Activity in the ^{58}Ni + Pt Reaction at 330 MeV [Marinov]
A. Marinov, S. Gelberg, Hebrew University; (B. Back, T. Happ, W. Kutschera, J. Schiffer)

(24) Deexcitation of Strongly-Deformed Fragments in Ni + Sn [Wolfs]
P. Benet, Purdue University; (F. Wolfs, K. E. Rehm, R. V. F. Janssens, E. F. Moore, M. Carpenter, A. Wuosmaa)

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

(26) Search for Evidence of Octupole Deformation at Scission in the Symmetric Fission Fragments from ^{56}Ni [Sanders]
S. Sanders, F. Prosser, K. Farrer, A. Hasad, University of Kansas; K. Beard, University of Notre Dame; P. Benet, Purdue University; (F. Wolfs, A. Wuosmaa, R. V. F. Janssens, T. L. Khoo, M. Carpenter, E. F. Moore, R. R. Betts, B. Back, D. Henderson)

(27) In-Beam Tests of the Large-Area Scintillation Telescope [Piercey]
R. Piercey, T. Dybler, Mississippi State University; A. Ramayya, Vanderbilt University; (C. Davids, B. Back)

(28) Slope Anomalies in ^{58}Ni+Sm One- and Two-Neutron Transfer Reactions, Part II [Betts]
A. Smith, University of Oxford; (R. Betts, E. F. Moore, K.E. Rehm)

b. Outside Users of ATLAS and of ATLAS Technology During the Period January 1 - December 31, 1989

This list includes only those who were present at ATLAS for an experiment. A star denotes students.

(1) University of Kansas
F. Prosser
S. Sanders
* K. Farrer
* A. Hasad

(2) University of Notre Dame
U. Garg
K. Beard
* D. Ye
J. LaVerne
R. Schuler
J. Kolata
* R. Kryger
* R. Tighe
* L. Chung
* S. Dixit

(3) Purdue University
P. Daly
Z. Grabowski
M. Quader
P. Benet
* I. Bearden
* B. Brackney

(4) Idaho National Engineering Lab
M. Drigert

(5) Vanderbilt University
C. Maguire
A. Ramayya
* D. Oliver
* A. Vabishi
* R. Clark

(6) Oak Ridge National Lab
* J. Shea

(7) Western Michigan University
J. Tanis
S. Ferguson
E. Bernstein
K. Lifrieri

(8) Lawrence Livermore National Lab
D. Schneider
M. Clark
T. Wang

(9) Lawrence Berkeley Lab
K. Berkner

(10) University of Rochester
M. Hass

(11) University of Richmond
M. Vineyard
J. Gilfoyle
* R. Trotter
* S. Sigworth

(12) Texas A&M University
D. Church

(13) Indiana University
K. Kwiatkowski
J. Wile
* S. Yenello
* D. Field
V. Viola

(14) University of Toledo
L. Curtis

(15) Hope College
P. DeYoung
* J. Sarafa
* C. Copey

(16) JAERI, Japan
H. Ikezoe

(17) Carnegie-Mellon University
M. Kaplan
* E. Vardaci
* D. Moses
* W. Parker
P. Karol

(18) University of Manchester
W. Phillips
J. Durell
* J. Fitzgerald
* A. Mowbray

(19) University of Giessen
W. Kühn

(20) Yale University
P. Parker
* M. Smith
* P. Magnes
* K. Hahn
* R. Curley
K. Lister
P. Chowdhury
J. Greenberg

(21) Rutgers University
J. Cizewski
N. Koeller

(22) University of Florida
R. Piercey
* T. Dydler

(23) University of Tennessee
L. Riedinger

(24) University of Oxford
A. Smith

(25) Daresbury Laboratory
J. Lilley

(26) Queens University
W. Graham

(27) Hebrew University
A. Marinov
S. Gelberg
M. Paul

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

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

(30) University of Sao Paulo
J. Ordonez
J. Codeco

(31) Michigan State University
S. Austin
E. Kashy
M. Maier
D. Mikolas
J. Winfield

(32) Princeton University
F. Calaprice
A. Hallin

c. Summaries of the Continuing User Programs, January 1 - December 31, 1989

c.1. The University of Notre Dame

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

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 a study of the $^{16}O+^{27}Al$ system was continued as part of a collaboration with Hope College. In this experiment neutrons, as well as light-charged particles were detected in coincidence with heavy fragments.

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. Programs helping with the setup of the gamma-ray facility have also been developed. Additionally, part of the Notre Dame group is currently developing and constructing a Bragg-curve detector for use in the focal plane of the fragment mass analyzer. In-beam tests were carried out in the past year.

ii. Atomic Physics (A. E. Livingston, A. D. Zacarias, G. Serpa)

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. A measurement of the 2^3S_1-2^3P_0 transition energy in helium-like Ni^{26+} is also planned for the coming year. Precise measurements of 2s-2p transition energies in simple (few-electron) atomic systems provide stringent tests of several classes of current atomic-structure calculations. The group is also participating in a measurement of the lifetimes of the 2^3S_1 state in helium-like bromine. 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.

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 ^{58}Ni projectiles at ATLAS energies to complete the original measurements. The first experiments using a Fricke dosimeter with a 295-650 MeV ^{58}Ni beams were successfully carried out.

c.2. Purdue University (P. Daly, Z. Grabowski, P. Benet, and I. Bearden)

The Purdue University group, including several thesis students, is working on high-spin nuclear states at ATLAS. 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. In particular, a study of ^{143}Eu and ^{144}Gd is underway. 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.

A member of the group is currently based at Argonne in order to facilitate interactions with the local group and to speed up the analysis effort. The group has also initiated a new direction in research where gamma-ray techniques are used to derive information on the cross section for deep-inelastic and transfer channels in the vicinity of the Coulomb barrier. The group plans to use these types of reactions to perform spectroscopy studies on neutron nuclei with Z=50 that cannot be studied by another means.

c.3. University of Kansas
(F. W. Prosser, S. Sanders, K. Farrer, and A. Hasad)

The group continued an effort in the understanding of fission in very light systems (near A=56) with further particle-γ coincidence measurements. In the past year an experiment was carried out to confirm the results from an earlier measurement in the ^{32}S + ^{24}Mg system. In the previous measurements the ^{28}Si channel was found to show indications of preferential population of octupole deformed states. Analysis of this data is currently underway. It is expected that the reaction study will be extended to other dominant exit channels, e.g. ^{24}Mg. The new experiment was designed to improve the coincidence efficiency by improving the particle detector geometry. This required the design and construction by the group of a new particle chamber for the BGO gamma-ray facility. The new chamber allows for much improved flexibility in the positioning of large gas counters and detector arrays. It incorporates the same large flange design as used on the 36" scattering chamber at ATLAS. This allows the use of the same hardware (large detectors, extension boxes and feed-thru flanges) on both chambers. The group is also currently constructing a very large-area Bragg-curve spectrometer for use in particle-gamma coincidence experiments.

The study of the pulse-height defect in silicon detectors was continued. 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 were intended to extend previous measurements to higher energies and are 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 calcium has been initiated. 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. 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, a run was 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 MeV. The beams were delivered to the atomic physics beam line. This test run demonstrated the capability of ATLAS for producing the decelerated beams needed for the measurement of the 2p→1s transitions in helium-like calcium. 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 2^3S_1 state in helium-like bromine. This measurement is an important test of relativistic quantum mechanics. They also participated in an experiment to verify the hyperfine quenching effect for the $^3P_0$ level in helium-like nickel. 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. The University of Manchester (W. R. Phillips, J. L. Durell, J. B. Fitzgerald, M. A. C. Hotchkis, and A. S. Mowbray)

The group from the University of Manchester (England) is working on the spectroscopy of very neutron-rich nuclei. These nuclei cannot be produced with the usual fusion-evaporation reactions and the information is derived from prompt γ-γ coincidence measurements of fission fragments. The fissioning nuclei are either obtained from a nuclear reaction using ATLAS beams or from a fission source prepared in the hot chemistry laboratories of the Chemistry Division at Argonne. In all cases the measurements take advantage of the detection sensitivity of the Argonne-Notre Dame BGO γ-ray facility where the Compton-suppressed spectrometers are used for the discrete γ-ray spectroscopy while the 50-element BGO array provides multiplicity and sum-energy. This information can be used in studies of the global properties of the fission fragments such as energy sharing and angular momentum transfer to the fragments. The main current interest is in the study of a new region of octupole deformation around ^{146}Ba discovered at Argonne with this technique as well as in very deformed neutron-rich nuclei around ^{102}Zr.

c.7. Idaho National Engineering Laboratory (M. W. Drigert)

Dr. Drigert has been associated with most of the research programs done with the Argonne-Notre Dame BGO γ-ray facility. Within the collaboration he is assuming the responsibility of maintenance and continuous upgrade of the software used to analyze the data taken with the facility. The principal tasks performed by the computer programs are: (1) data reduction; (2) construction of γ-γ matrices; (3) projection of coincidence data and/or analysis in two dimensions; (4) analysis of one-dimensional spectra, etc. Dr. Drigert is mainly interested in the study of superdeformation. He has been working mostly on the nuclei ^{151}Dy and ^{190}Hg (see description elsewhere in this report). He is also studying the properties of actinide nuclei close to the region of octupole stability near ^{222}Th. His efforts in the region concentrate on ^{219}Ac.

c.8. University of Western Michigan, Lawrence Berkeley Laboratory and Lawrence Livermore National Laboratory (J. Tanis, E. Bernstein, S. Ferguson, K. Berkner, D. Schneider, W. Graham, and M. Clark)

This group is studying the channeling of heavy ions between the ordered rows of a crystal lattice where small-impact-parameter collisions with target atoms are reduced considerably. As a result, atomic excitation and charge-changing probabilities are altered significantly from expectations based on collisions in amorphous solids or in gaseous targets. Even more striking, hyperchanneled ions (ions whose low transverse momenta cause their motions to be limited to a single axial channel) exhibit an anomalously high probability for maintaining their initial charge state in moving through crystals many times thicker than amorphous targets of equilibrium thickness. These so-called "frozen" charge states represent that fraction of the beam which is hyperchanneled and thus avoid close collisions with the target atoms.

During the past year, two experiments were conducted exploiting the narrow energy resolution of ATLAS to study dielectronic recombination (DR). Accurate measurements of state-selective DR cross sections can provide stringent tests of atomic structure calculations in heavy few-electron systems but have heretofore been impractical. The first experiment involved high-resolution measurements of the energy loss and corresponding charge-changing probabilities of 267-320-MeV Ti^{19+} and Ti^{20+} ions channeled along the <110> axis of a thin (400-Å) gold crystal. By separating the hyperchanneled particles through their energy loss (with the area III spectrograph), it was found that the best-channeled ions demonstrated dramatically enhanced probabilities for electron capture in the region of projectile velocity corresponding to the capture of free electrons. The widths of the observed resonances were exceedingly narrow (nearly an order of magnitude sharper than those observed previously in similar experiments on H_2 targets). In order to elucidate the Z-dependence of this energy shift, we conducted a second experiment to reproduce this effect with He-like and Li-like Ca ions. Because of difficulties with the beam energy resolution, the resonance widths were quite broad, however it appears that the energy shift is comparable to that observed with Ti.

These results have caused several of the older low-resolution experiments to be reanalyzed and there now appears to be a systematic trend emerging. This effect had never been detected before because of the broad widths of the obseverved resonances in those earlier poor resolution measurements. Two possibile sources for this shift which are now being explored are the effects of the perturbative treatment of the Breit interaction used in the Multi-Configuration Dirac Fock (MCDF) calculations of the Auger energies and the impulse approximation used to estimate the DR cross sections.

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 at other laboratories.

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 we continue to interact with personnel concerning ongoing refinements in the technology. Topics in which we have been involved during the past year are (1) a change in the method of cooling the FSU resonators and (2) the transfer of information about our new fast tuner.

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

Argonne has fabricated 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 occasionally since then to assemble and test the resonators. Also, there is a continuing active interchange of technical information between ANL and KSU. Recently, the high-field performance of a phase-controlled β=0.065 split-ring resonator was studied by a collaborative team working at Argonne.

d.3. University of Sao Paulo

Argonne has agreed to assist the University of Sao Paulo (USP) in the construction of a small superconducting heavy-ion linac to serve as an energy booster for projectiles from their 8-MV tandem. This booster will be similar in many respects to the ANL booster linac built in the late 1970s. The ANL contribution to this project will be (1) to build (at USP expense) 12 split-ring niobium resonators, (2) to provide technical information, and (3) to train USP staff members in several phases of superconducting-linac technology.

Although the generalities of this plan have been agreed upon for several years, the fabriciation of components has not yet started because of delays in the formal international arrangements and the release of funds. However, it is now expected that fabrication will be able to start by mid FY 1990. In the meantime, two Brazilian engineers are working at Argonne gaining experience in cryogenics and in superconducting-resonator technology.

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

In order to increase the level of minority involvement in nuclear physics, it is necessary to interact with a large number of qualified students and faculty members. During the past year there have been concentrated efforts to identify sources of minority students and generate interactions with them. These efforts have succeeded in attracting a number of qualified students to apply for participation in the programs of the ANL Physics Division.

Initial efforts were directed toward the identification of institutions with relatively strong physics programs and with faculty interested in stimu-lating their students to pursue research activities and summer programs. In a number of cases it was possible to visit the college, meet faculty members, and discuss both physics and opportunities with students and faculty. During these visits lectures were presented and were followed by discussion of activities in nuclear physics, at Argonne and other national laboratories, and the possibilities for graduate study, employment, etc.

Additional activities included sending letters and descriptive material to the homes of student awardees of APS minority scholarships, and attending meetings of the Society for the Advancement of Chicanos and Native Americans in Science and of the Society of Black Physics Students.

As a result of these efforts, 12 applications were received for the summer program and one student received a NPSC award that includes summer research in the ANL Physics program. Among the twelve applicants were one Hispanic and one American Indian. A total of 6 offers were made for the Summer Research Participation program in conjunction with Argonne's Department of Educational Programs. Many students indicated interest in participating in the programs, but were already committed for the year. The program this past year was the first time such an effort has been made by this Division and, as a result, required considerable start-up effort. The program was resumed early in FY 1990 with return visits to some of the institutions that had been targeted previously. While it is too early to determine the results for FY 1990, the response by both faculty and students at these schools has been much more enthusiastic than earlier. Additional institutions will be visited during this year and several meetings of minority groups will be attended. It is hoped that these ongoing interactions will, in time, generate institutional relationships that will enrich the physics programs in minority institutions and substantially enhance minority involvement in nuclear physics.

D. SUPERCONDUCTING LINAC DEVELOPMENT

This developmental program is concerned with the general aspects of superconducting technology for the acceleration of heavy ions. The choice of work is now guided by remaining questions about the technology of ATLAS and especially by the requirements for the positive-ion injector for ATLAS. Most of the work falls within the following topics: (a) superconducting accelerating structures, (b) electron-cyclotron-resonance heavy-ion source, (c) beam-control techniques, (d) beam-diagnostic techniques, and (e) time-of-flight technology for pulsed beams, including bunching.

An extension of the program into a new area of work is starting in 1990. This activity consists of investigations of some basic properties of RF superconductivity, in contrast to developmental effort aimed at immediate applications. The emphasis of the basic studies will be on the low-frequency range of special importance for low-velocity accelerating structures, but the results obtained are expected to be of general interest for all of RF superconductivity.

a. Status of the Positive-Ion Injector

The new positive-ion injector (PII) consists of an electron-cyclotron-resonance ion source (ECR) on a voltage platform followed by a new class of superconducting injector linac. Multiply-charged ions from the source are transported to the injector linac by way of a beam preparation system that includes two stages of magnetic analysis and two stages of bunching.

When completed in early 1991, the injector linac will consist of 18 four-gap accelerating structures housed in three cryostats. The interior of the one of the cryostats is pictured in Fig. II-3. The nominal accelerating voltage of the 18-structure array is 12 MV. Because of the modular nature of the resonators, this new injector system has become useful long before the whole linac is completed.

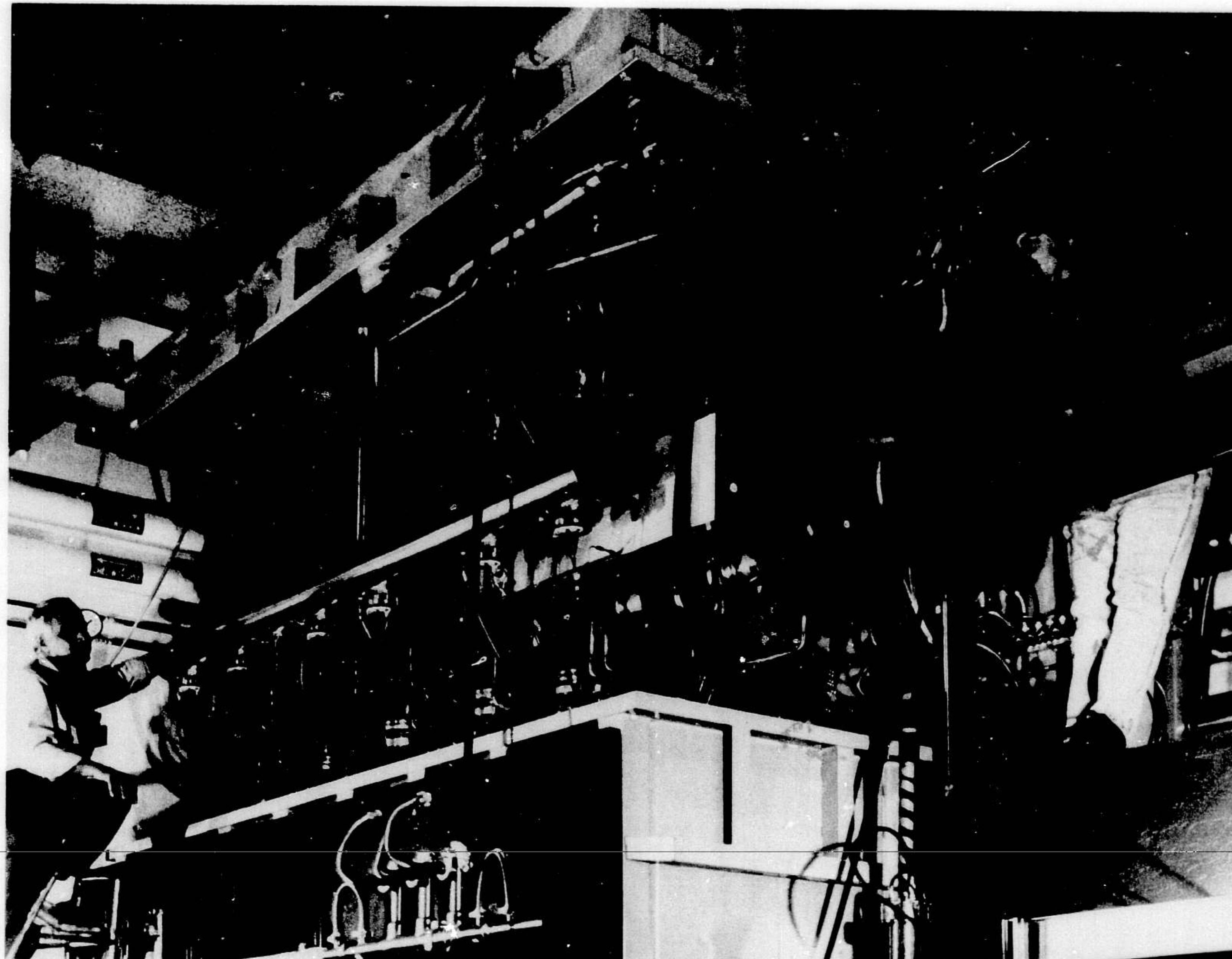

Fig. II-3. View of one of the acceleration sections of the PII linac being lowered into its cryostat.

The current status of PII is as follows. All parts of the system have been completed and thoroughly tested except for the injector linac. A 3-MV version of the linac was first operated for beam acceleration in March 1989 and, following this successful test, was then used occasionally until early December to provide accelerated ions for research. A 7-MV version of the linac was then installed and was tested in April 1990; the accelerating voltage will be increased to 8 MV in late summer, 1990. The complete 12-MV system will be assembled in late 1990 and undergo beam-acceleration tests in early 1991.

Beginning in early summer, 1990, PII will be used regularly as the injector for ATLAS, first for ions with A<150 and then gradually extending the mass range up to uranium by mid 1991.

b. Technology of PII

This section gives a brief summary of the technology of PII, with emphasis on work that has not been reported in previous annual reports. More detail about parts of the technology is given in ANL-89/11, the 1989 Physics Division Annual Review.

1. Injector Linac
(K. W. Shepard, G. P. Zinkann, B. E. Clifft,* and P. Markovich)

Resonators. Four kinds of superconducting resonators are used in PII. Each one is an interdigital 4-gap structure driven by a quarter-wave line. All four types have been thoroughly tested both off and on line. The average accelerating fields for the on-line units tested to date is turning out to be somewhat greater than the design value of 3.0 MV/m. Note that, because of geometrical factors, an accelerating field of 3 MV/m in our low-β units is equivalent to 6 MV/m in a cavity for β=1 particles, with respect to maximum surface electric field.

*Chemistry Division, ANL.

The main technical developments during the past year have been those associated with installing the new resonators in a cryostat and correcting the problems revealed by beam-acceleration tests. The most significant developments of this kind were (a) a change in design required to eliminate a leak-prone indium seal on the resonator housing and (b) the design and installation of a more-positive support structure within the cryostat. Both design changes were successful.

By March 1990, 12 of the injector resonators have been completed and the remaining 6 are more than half completed. All of the 10 resonators that have been tested off line operate stably at accelerating fields well above the design values.

Another encouraging experience with the on-line resonators is that phase control has not been a serious problem. Only the first unit (which has exceptionally small electrode-to-electrode gaps) has caused some trouble. The good performance results partly from the greater control power of the new fast tuners (see below) and partly from the inherent mechanical rigidity of the structure.

Cryostats. Two of the three large cryostats of the injector linac have been built, assembled with resonators, and operated on line. The measured heat leak for an assembled cryostat is about 25 W. This is somewhat greater than was expected but is satisfactory. The overall design concept is proving to be sound and it has not been necessary or desirable to make any costly changes in design.

The third cryostat is now being assembled off line.

RF Control Electronics. As discussed in last year's report, new fast turners and RF control modules have been developed for PII and a good RF power amplifier has been procured. All of this equipment has now been tested with on-line operation of resonators, and the performance is excellent.

The new fast tuners developed for PII are being used to upgrade the performance of the main ATLAS linac.

2. Distribution of Cryogens (L. M. Bollinger and J. M. Nixon*)

Liquid-Helium System. The 100-W helium refrigerator installed in 1987 for the cooling of PII has been replaced by a 300-W unit that is on loan from the MHD program. In principle, this borrowed refrigerator could be recalled. If this were to happen, it would be a crisis for the operation of ATLAS, since the total heat load of PII is expected to be >200 W.

The complete LHe cryogenic system, including the distribution line, has worked well in the cooling of the on-line cryostats of PII.

Liquid-Nitrogen System. The LN_2 distribution system for PII has been completed and is operational. Unexpectedly, it proved necessary to install a phase separator and pressure-control system on the LN_2 line in order to ensure reliable operation of the PII cryostats. This requirement generated a substantial unplanned expense.

3. ECR Source and Voltage Platform (R. C. Pardo, P. J. Billquist, and (J. M. Bogaty)

The ECR source has been used regularly during the past year for a variety of purposes, including providing beams of ^{3}He, ^{13}C, ^{40}Ar, and ^{86}Kr for acceleration through ATLAS. The performance was generally satisfactory. A highlight of the work was the production of a uranium beam with UF_6 as the feed material. The charge-state spectrum, which is given in Fig. II-4, is consistent with our expectations and with the experience of others for very heavy elements such as tungsten. This result provides assurance that our earlier projections of ATLAS performance for uranium will be realized.

The energy spread of beams of ^{11}B from the source have been measured by a laser method. The result is in the range 7-10 eV per charge, depending on operating conditions. Again, this is consistent with the experience of others.

Considerable effort has been devoted to problems created by the isolation transformers associated with the voltage platform. These transformers have failed and have been repaired (at the vendor's expense) several times. Since

*Engineering Physics Division, ANL.

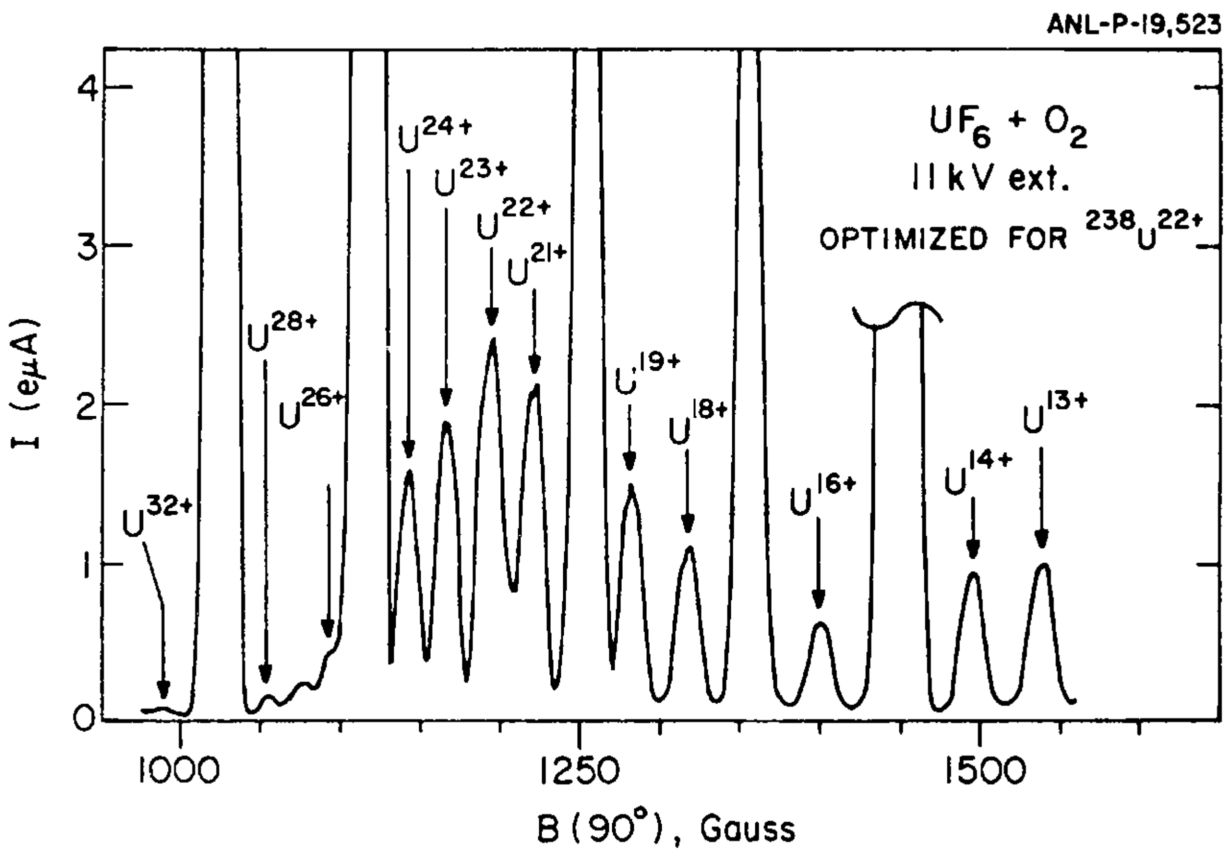

Fig. II-4. Magnetic-rigidity spectrum of uranium ions from the ECR source.

one such failure in mid-1989, the platform voltage has been limited to 250 kV rather than the design value of 350 kV. In January 1990, however, we undertook to determine whether or not the transformers could operate at 350 kV. Over a period of a week, the voltage was gradually pushed up to 325 kV, at which voltage it operated stably for a day. Then the leakage current began to increase and sparking was observed in a somewhat different form than had been experienced previously. Although the nature of the sparking was not determined, it was decided not to push the transformers to destruction.

The voltage is again being limited to 250 kV, and a set of transformers of improved design has been ordered. Fortunately, a voltage of 250 kV is adequate for all ions that can be accelerated by PII during 1990.

Although initially the platform voltage was stable enough for our needs, the voltage ripple has now increased enough (~90 V) to cause beam-pulse broadening, probably because of changes in the isolation transformers. A voltage-stabilizing system has been designed, built, and recently installed. It reduces the voltage ripple to a fraction of a volt.

4. Beam Transport and Beam Preparation Systems

(P. K. Den Hartog, R. C. Pardo, J. M. Bogaty, L. M. Bollinger, B. E. Clifft,* and K. W. Shepard)

The ion beams transmitted to the injector linac must be magnetically analyzed with good resolution and must be well bunched. Both requirements are rather demanding because of the very low velocity ($\beta \approx 0.01$) of the beam.

Magnetic Analysis. The charge-to-mass ratio q/A of the beam from the ECR source is analyzed by two magnets. A 90° magnet on the voltage platform has a resolution width of 1% and, at ground potential, the first 90° magnet of an isochronous pair can be operated as an energy analyzer with a nominal resolution width of 0.1%. Because of the energy spread induced by the bunching on the voltage platform, in practice the second analyzer is used typically with a resolution width of ~0.3%. Both magnetic analyzers perform as designed.

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Beam Bunching. A two-stage bunching system transforms the d.c. beam from the ECR source into pulses << 1 ns wide at the first resonator of the injector linac. The overall bunching efficiency is about 60% at a beam-pulse frequency of 12.125 MHz. The first buncher (on the voltage platform) is a gridded gap with a saw-tooth-like wave form, and the second buncher (at ground potential near the injector linac) is a spiral-loaded 2-gap accelerating structure. Both bunchers are room-temperature devices.

The complete bunching system was used often during 1989-1990 and, as far as could be determined, both bunchers performed as planned. It has not yet been possible to assess accurately the extent to which the long beam line between source and linac is isochronous, because pulse broadening that might result from unequal path lengths is obscured by the influence of platform-voltage ripple. In any case, the observed bunches are narrow enough to preserve the longitudinal beam quality in PII.

Beam Chopping. Since the bunching system does not bunch about 30% of the ions accelerated from the voltage platform, one needs some way to remove ions that arrive at the injector linac with the wrong phase. In most bunching systems this is done with a beam chopper. However, beam tests have shown that this is not a satisfactory approach for PII because the energy spread induced by the fringing fields of the chopper is a serious source of beam-quality degradation. This well-understood effect, which is usually unimportant, has a major impact on the PII beam because its initial energy spread is so small.

Fortunately, there is an easy solution to the problem of removing unbunched ions. Because of the correlation between beam energy and time, the second-stage magnetic analyzer can be used to remove unbunched ions near the main beam pulse, and then the chopper can remove more distant ions without inducing much energy spread for the bunched beam. As far as we know, this simple but effective approach has not been consciously used previously in a bunching system.

5. Beam Diagnostics (J. M. Bogaty, R. C. Pardo, and K. W. Shepard)

Refined diagnostic tools are needed to achieve optimum beam bunching in PII and thus to preserve the excellent beam quality of the ECR source. The heavy-ion detectors normally used to measure energy and time distributions are ineffective because of the low velocity and heavy mass of the ions involved. Consequently, we have concentrated on diagnostic techniques that measure time spectra with two new kinds of detectors.

Single-Wire Detector. This detector is designed to sample, with good time resolution, the arrival time of individual ions in the beam. A very fine wire (10 μ) mounted in the beam is the interaction target. Each ion striking the wire produces a burst of electrons, which are accelerated radially by a coaxial anode and some of which pass through an aperture into a channel-plate detector. Because of the axial geometry, the time resolution of this detector should be much better than is required for PII.

The performance of the single-wire detector is as expected. Beam pulses as narrow as 130 ps have been measured and this measured value is almost surely dominated by the beam-pulse width. A drawback of the detector is that the beam intensity must be attenuated by a large factor in order to limit the counting rate.

Fast Faraday Cup. This detector is designed to measure directly the time distribution of beam current. The time response of most current probes is poor for slow-moving heavy ions because of the signal induced on the probe while the ion approaches. In our fast Faraday cup, this effect is minimized by shielding the probe with a grid that is only 0.3 mm from the probe. Thus, the probe senses the moving ion for only a very short time.

The basic structure of the fast Faraday cup is in the form of a 24-ohm strip line. Great care was taken to preserve the 24-ohm impedance throughout the line, including at the detection cup. Thus, the line has wide-band response up to very high frequencies (10 GHz) and the effective time resolution of the system is limited mainly by the frequency response of the electronics available to us. Beam pulses as narrow as 400 ps have been observed and much better resolutions would immediately be obtained with better electronics.

This work is continuing with the expectation that faster rise times and greater sensitivity can be achieved. We expect that detectors of this kind will prove to be very useful for tuning the bunched beams provided to users.

Diagnostic Detectors Within Cryostats. In order to optimize the matching of beam phase space to the injector linac, two types of detectors are being installed inside of the first PII cryostat, near the first resonator. One of these units is a fast Faraday cup, designed to make it easier to tune the parameters of the bunching system. The second detector is a four-quadrant aperture designed to help in the adjustment of the transverse phase space of the incident beam. These are the first beam-diagnostic tools that we have used within the cold regions of a cryostat, and it may be the first such use anywhere.

c. Beam Acceleration Experience (R. C. Pardo, P. K. Den Hartog, L. M. Bollinger, P. J. Billquist, J. M. Bogaty, B. E. Clifft,* K. W. Shepard, and G. P. Zinkann)

The first acceleration test of PII was carried out in March 1989, with a beam of $^{40}Ar^{12+}$ ions from the ECR ion source injected into the injector linac. This prototype version of the linac provided 3 MV of acceleration from five resonators mounted in one cryostat. Since that first run, which was highly successful, PII has been used as the injector of ATLAS on a number of occasions. The beams accelerated are $^{3}He^{2+}$, $^{40}Ar^{12+}$, $^{86}Kr^{19+}$ and $^{13}C^{3+}$, where the ^{13}C beam was used to tune ATLAS so as to accelerate the unstable nuclide ^{39}Ar. The ^{3}He and ^{39}Ar beams were used in physics research. The 3-MV version of the PII linac was removed from operation in December 1989 in order to add the second section to the injector linac. This enlarged 7-MV version of the injector linac was installed in early 1990 and successfully tested in April 1990 by the acceleration of $^{86}Kr^{15+}$.

Results for the first acceleration test with the 3-MV injector linac were given in last year's report. Here we summarize the results for all operating experience, most of which took place during the past year.

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ECR Ion Source. The source has often been operated stably for long periods (days) with only minor adjustments of parameters. We do not yet have enough experience with routine operation to know how rapidly one can expect to switch from one kind of beam to another.

Because our users require exceptionally good beam quality and pure beams, contaminants of various kinds in the accelerated beam could be a problem. In an accelerator mass spectroscopy experiment it was shown that, under appropriate operating conditions, the background level of ions from structural materials in the ECR source was exceptionally low, $\lesssim 10^{-8}$ of the main beam.

Beam Bunching. Both the first-stage and second-stage bunchers operated stably over long periods of time. The measured pulse widths are influenced by several factors but are consistent with what was expected. There is every reason to believe that the bunching system itself is satisfactory in all respects.

Pulse widths produced by the first buncher were measured with a fast Faraday cup (see D.b.5.) located near the voltage platform. These widths ranged from 0.4 to 0.8 ns for a ^{86}Kr beam, depending on source operating conditions. The corresponding widths were greater (~3 ns) when measured near the injector linac, but this pulse broadening results from voltage ripple on the source platform, a problem that was later corrected.

The second-stage buncher is used to compress the beam pulses to the width required by the injector linac, typically 0.3 ns. Pulses as narrow as 130 ps have been measured with the single-wire detector at the entrance to the linac.

Transverse Emittance. The measured transmission of a 2.44-MeV $^{40}Ar^{12+}$ beam through two widely spaced apertures indicates that $\epsilon_x \approx \epsilon_y \approx 12$ mm-mrad. This is about what was expected and gives a normalized emittance that is about the same as a tandem beam for ions in the same mass range. We do not yet have any systematic data on how ϵ depends on the ion species, but the impression gained by tuning beams from ^3He through ^{86}Kr is that there is no strong dependence.

Longitudinal Emittance. The longitudinal emittance ϵ_z can be determined reliably by measuring the time distribution or, if feasible, the energy distributions under two appropriate conditions. We do not yet have an extensive set of results for ϵ_z, but the measurements that have been made indicate that the longitudinal emittance of the beam from PII is substantially better than that from a tandem with a foil stripper in the terminal. This improvement should provide important new research capabilities for experimenters.

The longitudinal emittance of a $^{40}Ar^{12+}$ beam was measured both before and after acceleration through the injector 3-MV linac. Before acceleration, $\epsilon_z \approx 4\pi$ keV-ns when the full beam current was 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 acceleration. This procedure reduces beam intensity, of course, but it is often useful because the ECR source provides more beam than is needed.

After acceleration through PII, the measured emittance of the $^{40}Ar^{12+}$ beam was $\epsilon_z \approx 5$ keV-ns; and at the output of the booster, for the $^3He^{2+}$ beam we measured $\epsilon_z \lesssim 1\pi$ keV-ns. Both values are remarkably small.

With the 7-MV injector linac,the measured value of ϵ_z for a 400-MeV beam in the experimental areas was 16π keV-ns. This value is substantially smaller than had been observed for any beam from the tandem in the same mass range. Indeed, all of the values of ϵ_z measured to date indicate that PII is establishing a new standard of excellence for the longitudinal beam quality of heavy-ion beams.

Injector Linac. In all of the various runs with the 3-MV and 7-MV versions of the PII linac the resonators operated stably over a period of many days. In every case the resonators were capable of providing a total accelerating voltage greater than the design value, although they were not always operated this way because of the desirability of adjusting the accelerating fields to be appropriate for the q/A of the ion.

One very satisfying aspect of all of the beam tests was the high degree of stability of the whole system, including ion source, beam transport and analysis system, bunchers, injector linac, and cryogenic system. As a result, we were able to tune the beam through the system, turn it off, and then return to the same operating conditions some days later without much effort.

The one disappointment in the first beam test was the poor beam transmission of the linac. This problem was largely eliminated for the following runs by improving the alignment of linac resonators and by using more appropriate operating parameters for the focussing solenoids. However, since the transmission was still only ~60%, internal diagnostics are being installed in the cryostat (see D.5.) to help understand why the transmission is not 100%, as it should be. It seems probable that at least part of the problem results from a poor vacuum caused by a helium leak in the first cryostat, where the ion velocity is low and thus charge-exchange cross sections are high.

A principle concern about the PII linac has been that the longitudinal optics would be very difficult to adjust because of the large changes in relative velocity of the beam in the first few resonators. In practice, this was not a problem and indeed the freedom from beam steering by the resonators makes the linac easy to tune.

Conclusions

We had expected that the serious problems with PII, if any, would be associated with either the need to bunch very slow-moving heavy ions or with the beam optics at the front end of the injector linac. The operating experience to date has been so successful and so free from serious difficulties as to indicate that these potential problems are under control and that all of the 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.

E. BASIC TECHNOLOGY OF RF SUPERCONDUCTIVITY

This new area of investigation has started on a modest scale with support from Laboratory discretionary funds. There are two parts to this work. One is what is intended to be a continuing investigation of many aspects of the basic technology of RF superconductivity. The second part is a part-time collaboration with members of the Engineering Physics Division on topics of mutual interest, such as new kinds of superconducting accelerating structures.

a. Basic Technology Investigations (K. W. Shepard)

The initial focus of this new program is on increasing the limits of high-field operation of superconducting cavities. Of particular interest are phenomena causing electron loading, both multipacting and field emission, within superconducting resonators. Electron loading limits the performance of both low-velocity (ion) and high-velocity (electron) superconducting accelerating structures, but the dominating factors involved may be different because of large geometrical differences.

In order to be able to carry out these new investigations without interfering with the continuing needs of ATLAS, a resonator-test facility dedicated to the new program is being formed. The central element, a test cryostat, has been designed and fabricated, and assembly has started. Associated electronic and vacuum systems are being procured, and LHe and LN_2 from the PII distribution systems will soon be piped to the nearby test cryostat. This continuous availability of LHe will allow long-term tests to be carried out easily.

Experimental work with the new facility is expected to begin in late 1990.

b. Superconducting RFQ Development (J. R. Delayen,* and K. W. Shepard)

Very high surface electric fields have been achieved in the first tests of a superconducting RF quadrupole device. The experiments are being performed collaboratively by the Physics and the Engineering Physics Divisions. The RF quadrupole fields were generated between niobium vanes 6.5 cm in length, with a tip radius of 2 mm, and with an aperture of 6 mm diameter. The vanes were mounted in a modified ATLAS split-ring resonator, which provided a convenient means of generating a high RF voltage. The 64-MHz structure was tested at 4.2 K and operated cw at peak surface electric fields of 128 MV/m. Virtually no electron loading was observed at fields below 100 MV/m. It was possible to operate at surface fields of 210 MV/m in pulses of 1 msec duration. For the vane geometry tested, more than 10 square centimeters of surface support a field greater than 90% of the peak field. These fields correspond to 13 Kilpatrick for cw opeeration and 21 Kilpatrick for pulsed operation, fields more than a factor of two larger than so far reported for normally-conducting RFQ structures. This result indicates that superconducting RF technology may provide a new range of options for RFQ design.

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2.0-GeV VEPP-3 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. Another important initiative involves electron scattering experiments at the Saclay Linear Accelerator (ALS), and preparations for similar experiments at CEBAF. The work at ALS is concerned with the study of charged-pion electroproduction in deuterium and ^{3}He 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.

Weak interactions at low energy is the other 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 are planned as tests for the presence of induced currents and to provide new estimates of the strength of the vector-coupling constant. Laser trapping of radioactive atoms is also under study as a source for precision measurements of beta-decay asymmetries. A portion 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

During FY 1989 preliminary analysis in the Fermilab experiment on deep-inelastic muon scattering, E665, was completed on the data accumulated during the 8-month run in 1987-88. First results on ratios of xenon to deuterium cross sections, exclusive vector meson production cross sections, and hadron distributions were presented in preliminary form. These new data will provide valuable information on the A-dependence of hadron production and structure functions. Design work was completed and fabrication has begun on the new vertex drift chamber system which will increase the integrated luminosities to be obtained in the run beginning in February 1990 by more than an order of magnitude. The collaboration between the medium-energy physics group and staff of the Institute for Nuclear Physics at Novosibirsk completed the first phase of the program to measure the polarization effects in electron-deuteron interactions at the VEPP-3 electron storage ring. The results are in good agreement with the most widely-used models of the deuteron. Argonne will provide the storage cells and laser-driven polarized sources for the internal targets in all three phases of the experiment. The Novosibirsk group is responsible for the detector and storage-ring operation. Work continued on development of a high-density source which would be used in the final phase of the experiment and which would serve as a prototype for future programs at HERA and MIT-Bates.

The study of pion electroproduction in deuterium, a collaboration at the ALS-Saclay accelerator between the Argonne and Saclay staff has been completed. The results provide strong evidence that, even in the weakly-bound deuteron, multinucleon processes alter the electroproduction amplitudes in the forward direction. In addition to the ongoing research, Argonne staff has a strong participation in the development of the HERMES proposal to study the spin structure of the nucleon in polarization studies at HERA and in the development of the research program at CEBAF. At CEBAF, Argonne staff have assisted in the design of the high-momentum spectrometer, HMS, planned for Hall C, and the medium-energy physics group has proposed to assume responsibility for construction of a short-orbit hadron spectrometer. Argonne staff are spokesmen for four research proposals which were submitted to CEBAF and which would be appropriate for approval during the initial period of beam at CEBAF in 1994-95.

Argonne staff continue a limited involvement in studies at the Brookhaven National Laboratory AGS, which are aimed at exploring global properties in relativistic heavy-ion collisions under the condition of high-nuclear densities. Measurements emphasize inclusive spectra of emitted particles and two-particle correlations.

a. <u>Deep-Inelastic Muon Scattering from Nuclei with Hadron Detection</u>
(D. Geesaman, R. Gilman, H. Jackson, S. Kaufman, E. Kinney, D. Potterveld, 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 lepton scattering from nuclei 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. A new experiment, E665, using the Tevatron II at Fermi National Accelerator Laboratory provides 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

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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 data from other measurements. A schematic of the spectrometer system is presented in Fig. III-1.

A small-angle trigger has been added to the experiment to study deep-inelastic events at very low Q^2, down to 0.3 $(GeV/c)^2$. 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. For the 1990 run, Argonne is implementing the FASTBUS readout of the new vertex drift chambers.

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.

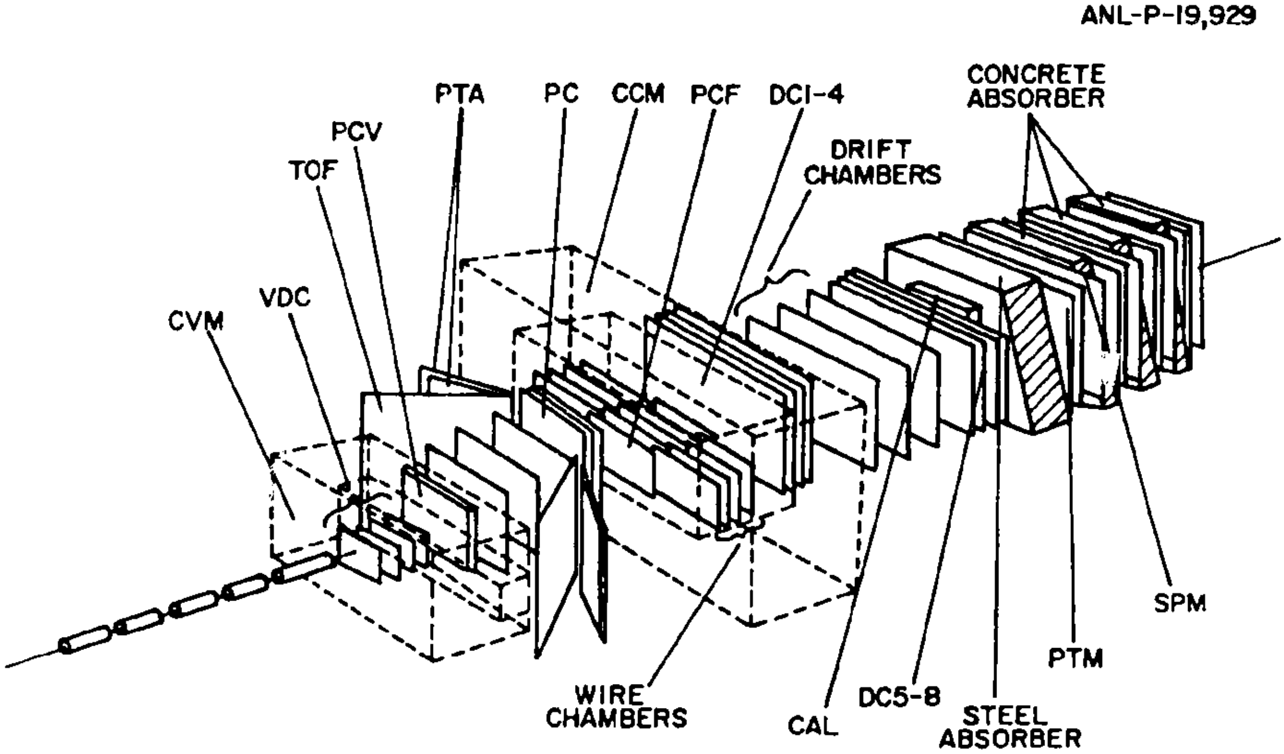

Fig. III-1. E665 experimental apparatus.

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). During 1989, production analysis of the 500-GeV data was completed and work continued on normalization and acceptance corrections. First results on the ratios of xenon-to-deuterium cross sections, exclusive vector meson production, and hadron distributions following deep inelastic scattering were presented at meetings. nData on the cross section ratios for xenon and deuterium are presented in Fig. III-2.

During the 1990 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 drift chambers is being constructed 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.

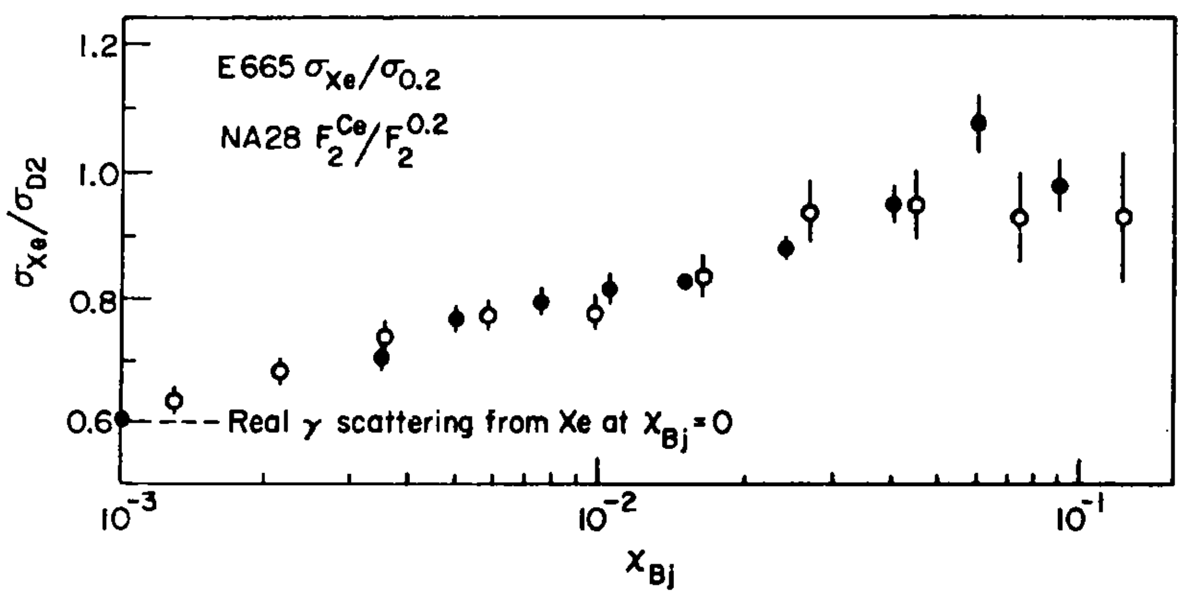

Fig. III-2. The ratio σ_{Xe}/σ_{D2} as a function of x_{Bj}. The data show that the cross section per nucleon for muon scattering on Xe is suppressed relative to that for D_2 in the region $0.001 < x_{Bj} < 0.1$. This phenomena, called "shadowing", has been seen in γ-nucleus scattering at high energies as well as in virtual photon scattering at low and high energies.

b. Electron-Deuteron Scattering With a Polarized Deuterium Gas Target in the VEPP-III Electron Storage Ring (R. J. Holt, K. Coulter, R. Gilman, E. R. Kinney, R. Kowalczyk, J. Napolitano, D. Potterveld, 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,* and B. B. Wojtsekhowski*)

An electron-deuteron scattering experiment was performed for the first time by using a polarized gas target contained in a storage cell in an electron storage ring. The tensor analyzing power T_{20} was measured up to a momentum transfer of 3 fm^{-1} at the 2-GeV electron storage ring (VEPP-3) at Novosibirsk. Data acquisition with the Phase I storage cell was completed. Analysis of the data is nearing completion and the preliminary results indicate good agreement with the most widely used models of the deuteron.

A high-density (Phase II) storage cell, also designed and constructed at Argonne, was installed in the VEPP-3 ring and tests with the electron beam were conducted. It was found that the reduction of beam lifetime was negligible and the background is tolerable with the new storage cell. Initially, the Phase II part of the experiment will be performed with the old Phase I detectors, since the new detectors (provided by Novosibirsk) will not be ready until the summer of 1990. Tests of this high-density storage cell are important not only for extending the present measurements to higher momentum transfer but also the characteristics of this cell are similar to that discussed for the HERA and MIT-Bates rings. The new target cell and detectors should permit measurements of T_{20} up to a momentum transfer of 4 fm^{-1}.

Although work on the laser-driven polarized deuterium source was diminished by the large effort expended on preparing and testing the Phase II storage cell, significant progress was made during the past year. We have achieved a vector polarization for deuterium of 30% with an intensity of 1×10^{17} atoms/s. This

*Institute for Nuclear Physics, Novosibirsk, USSR represents approximately a factor-of-two increase in polarization and intensity over previous tests and is due primarily to converting the source to optically pump Na rather than K atoms. The resonance fluorescence from Na is indicated in Fig. III-3 for Zeeman-induced transitions inboth Na and D and for $\sigma^{\pm}$ laser light. The polarization deduced[1] from these signals is p_z = 79% for Na and 38% for the deuterium nucleus when the intensity of deuterium atoms is 1×10^{17} atoms/s. Since the ratio of deuterium atoms in molecular form to those in atomic form was also measured, the net vector polarization is 30%. During the year, we plan to increase both the polarization and intensity of the source and explore the possibility of using an RF transition to enhance the tensor polarization.

[1]L. Young et al., Proceedings of the Topical Conference on Electronuclear Physics with Internal Targets, SLAC 1989, (World Scientific, Singapore 1990) p. 125.

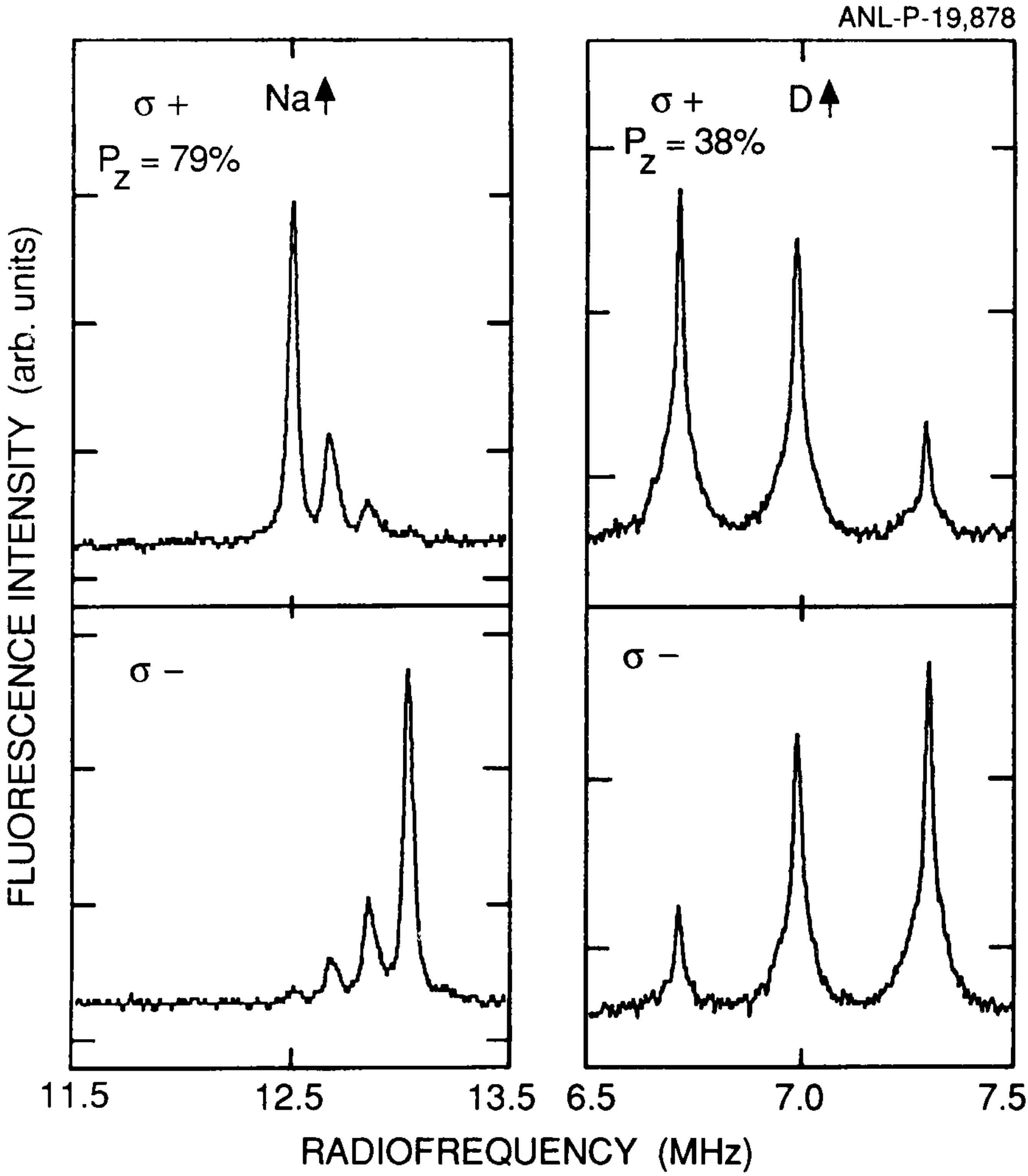

Fig. III-3. Resonance fluorescence from Na for RF-induced transitions in Na (left) and D (right) for both $\sigma^{\pm}$ optical pumping light.

c. <u>Photodisintegration of the Deuteron in the GeV Region</u>

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

The analysis of experiment NE8 at SLAC is in progress. The results at θ_{cm}=90° were found to have an energy dependence at the highest energies (E_γ=1.3-1.6 GeV) which is consistent with the quark counting rules and the reduced amplitude analysis. In addition, the data were found to be in disagreement with a meson-exchange model. These results were published.

The data at θ_{cm}=114° were found to support the trends discovered at θ_{cm}=90°. Again at the highest photon energies (E_γ=1.3-1.8 GeV), the cross section is consistent with the constituent counting rules. Analysis of the data at θ_{cm}=143° is in progress. At this angle the analysis is more difficult owing to a large two-step background, $D(\gamma,\pi^+)$, followed by the $D(\pi^+,2p)$ reaction. A Monte Carlo analysis was made with these reactions and it was found to be in agreement with the proton yield observed above the photon endpoint for the $D(\gamma,p)n$ reaction. It is expected that the analysis of all NE8 data will be completed during the year.

It is important 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 proposals to both NPAS and CEBAF as the only two possible avenues available to extend these studies to higher energy.

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d. Two-Body Photodisintegration of the Deuteron at Forward Angles and Photon Energies Between 1.5 and 4.0 GeV

(R. J. Holt, K. Coulter, S. J. Freedman, D. F. Geesamam, H. E. Jackson, S. Kaufman, E. Kinney, D. Krakauer, D. Potterveld, B. Zeidman, J. Napolitano,* R. Carlini,* R. Gilman,† R. E. Segel,‡ P. Bosted,§ E. Beise,¶ B. Filippone,¶ R. D. McKeown,¶ R. Milner,# D. Beck,** Z.-E. Meziani,†† R. Minehart,‡‡ and O. Keith Baker§§)

It was discovered in experiment NE8 at SLAC that the differential cross section for the $\gamma d \rightarrow pn$ reaction at the highest measured photon energies (E_γ=1.3-1.8 GeV) has an energy dependence consistent with the constituent counting rules and the reduced amplitude analysis. However, the energy range of this result is too small to argue that asymptotic scaling has been achieved. Thus, at CEbAF we have proposed to measure the differential cross section at forward angles for two of the simplest exclusive binary reactions involving a deuteron in the initial or final state: (1) $\gamma d \rightarrow pn$ between E_γ=1.5 and 4.0 GeV, and (2) $\gamma d \rightarrow \pi^0 d$ between E_γ=1.0 and 3.0 GeV.

The constituent counting rules predict an energy dependence of s^{-11} and s^{-13} for the $\gamma d \rightarrow pn$ and $\gamma d \rightarrow \pi^0 d$ cross sections, respectively, where s is the square of the energy in the center of mass. Since more complex nuclei involve more constituents and consequently a more rapid fall-off of the cross section as a function of s, these two cases may represent the only practical nuclear reactions that can be studied at large values of s where asymptotic scaling is most likely to be observed. These experiments are expected to be practical at high energies since a large beam current (~30 μA) and a large solid-angle spectrometer (HMS in Hall C) are expected to be available at CEBAF.

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e. Measurement of Proton Polarization in the d(γ,p)n Reaction

(R. J. Holt, K. Coulter, S. J. Freedman, D. F. Geesaman, H. E. Jackson, E. Kinney, D. Krakauer, D. Potterveld, B. Zeidman, E. Beise,* B. Filippone,* R. D. McKeown,* J. Napolitano,† R. Milner,‡ R. E. Segel,§ D. Beatty,¶ R. Gilman,¶ C. Glashausser,¶ G. Kumbartzki,¶ R. Ransome,¶ Z.-E. Meziani,# and D. Beck**)

A proposal was submitted to CEBAF to measure angular distributions of the proton polarization for the d($\gamma,\vec{p}$)n reaction in the GeV region. This proposed measurement will test the validity of extensions of conventional nuclear-physics theories to the higher energy regime. The results of the experiment will further constrain the suggestions from SLAC experiment NE8 that perhaps asymptotic scaling has been observed above a photon energy of 1.3 GeV. The experiment would make use of a polarimeter installed in either the High Resolution Spectrometer in Hall A or the Short Orbit Spectrometer in Hall C at CEBAF.

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f. <u>Proposal to Measure the Spin Structure Functions of the Proton and Neutron at HERA</u> (R. J. Holt, K. Coulter, S. J. Freedman, D. F. Geesaman, H. E. Jackson, E. Kinney, D. Potterveld, L. Young, B. Zeidman, E. J. Beise,* B. W. Filippone,* W. Lorenson,* R. K. McKeown,* C. E. Woodward,* I. G. Bird,† W. Brückner,† M. Düren,† H.-G. Gaul,†K. Kabuß,† B. Martin,† D. Nowotny,† B. Povh,† K. Rith,† C. Scholz,† E. Steffens,† H. Vogt,† K. Zapfe,† F. Zetsche,† C. N. Papanicolas,‡ S. E. Williamson,‡ R. Laszewski,‡ D. H. Beck,‡ J. Amann,§ H. Baer,§ J. McClelland,§ N. Tanaka,§ W. Haeberli,¶ K. Pitts,¶ S. Price,¶ T. Wise,¶ W. Korsch,# W. Luck,# J. van den Brand,** G. Dodson,** K. Dow,** K. Lee,** R. Milner,** R. Redwine,** G. Burleson,†† G. Kyle,†† A. Klein,†† G. Graw,‡‡ P. Schiemenz,‡‡ Z. E. Meziani,§§ M. Arneodo,¶¶ M. I. Ferrero,¶¶ S. Maselli,¶¶ C. Peroni,¶¶ A. Staiano,¶¶ P. J. Delheij,## L. G. Greeniaus,## O. Häusser,## R. Henderson,## P. Kitching,## C. A. Miller,## N. L. Rodning,## M. Vetterli,## R. Woloshyn,## R. Carlini,*** and J. Napolitano***)

The source of the nucleon spin is one of the most intriguing issues to emerge in the past several years. The simple SU(6) model of the proton can no longer reconcile recent spin structure function measurements at CERN with the notion that the proton spin arises from the valence quarks in the nucleon. This realization has led to a flurry of new models for the nucleon spin as well as speculation that some widely accepted rules (e.g. the Bjorken and Ellis-Jaffee sum rules) may not be obeyed.

It is absolutely essential to provide accurate measurements for both the proton and neutron spin structure functions in order to settle many of the issues. It

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is necessary to provide new data for the proton, since the CERN result is only two standard deviations from predictions of the conventional model and the Ellis-Jaffee sum rule. In addition, it is necessary to determine whether or not the simple quark model also breaks down for the neutron. With measurements of both proton and neutron spin-structure functions, it is possible to test the Bjorken sum rule as well. Thus, we have proposed to measure the proton and neutron spin-structure functions by using internal polarized H, D and ^3He gas targets in the 35-GeV HERA electron ring. The storage cell technology for polarized gas atoms which we developed for the Argonne-Novosibirsk collaborative experiment at Novosibirsk (see Sect. I.A.b.) will be employed at HERA. The experiment will also utilize the longitudinally polarized electrons which are expected to be available in the HERA ring.

During the past year much effort went into the preparation and submission of the proposal to DESY. Argonne led the preparation of the polarized target section of the proposal. Specific Argonne contributions to the proposal included target cell test results conducted at Novosibirsk and Argonne, computer simulations of beam-bunch induced depolarization of the target, computer simulations of storage cell performance, the laser-driven polarized source work, and design of the magnet wire chambers for the detector. The first hearing of this proposal by the Physics Research Council was conducted in early March at DESY.

g. Pion Electroproduction in Deuterium (H. E. Jackson, R. Gilman, R. J. Holt, E. Kinney, J. Specht, M. Bernheim,* J. Cheminaud,* J.-F. Danel,* G. Fournier,*, J.-M. LeGoff,* R. Letourneau,* A. Magnon,* J. Morgenstern,* C. Pasquier,* J. Picard,* D. Poizat,* B. Saghai,* P. Vermin,* M. Brussel,†, J.-P. Didelez,‡ M.-A. Duval,‡ R. Frascaria,‡ E. Warde,‡ and J.-C. Kim§)

To explore the use of pion electroproduction as a probe of multinucleon processes, we have performed a series of measurements on hydrogen and deuterium. The deuteron was chosen because, as the simplest nuclear system, it is a natural test case for any nuclear model. Observations were made for π^+ production on both targets for two values of the photon-nucleon invariant mass, W=1160 and 1232 MeV. π^- production on deuterium was also measured for W=1160 MeV. The kinematics corresponding to W=1160 MeV were chosen, because for this value of W the longitudinal virtual photon cross section for electroproduction on the proton is more than twice the transverse cross section, and quasifree scattering by virtual pions (the pion-pole term) is the largest longitudinal process. For forward-angle electron scattering angles such as those of the measurement reported here, the virtual photon has a strong longitudinal polarization, and the corresponding component is 0.6 of the total photon cross section. For the second kinematic configuration, which corresponds to W=1232 MeV, the amplitude for delta-production is enhanced. In both cases, the physics issue addressed is the extent to which the basic quasifree nucleon reaction is modified by the nuclear binding. The choice of the deuteron offered the advantage of use of a single cryogenic target for the two measurements. Because of the identical geometry, a direct comparison can be made of electroproduction on the proton in the deuteron to that of the free proton without the systematic errors common in absolute measurements.

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For all measurements, the incident beam energy was 645 MeV and the electron scattering angle was 36°. Electrons were observed in the ALS 900-MeV spectrometer and coincident pions in the ALS 600-MeV spectrometer which was set at 34°. For the ratio of the deuteron cross section for positive pions integrated over missing mass to the proton production cross section, we find:

$$R = 0.80 \pm 0.05 \qquad W = 1160 \text{ MeV}$$
$$R = 0.75 \pm 0.07 \qquad W = 1232 \text{ MeV} .$$

Forward-angle quenching may arise from modifications in the $n \to n\pi$ coupling by multinucleon processes in the bound system. The nucleon rescattering terms in which the pion is subsequently scattered by the photon into the continuum can enhance or suppress the longitudinal response of the nuclear system. Such a variation can be interpreted in terms of a pion excess arising from the exchange processes. At the lower virtual pion momenta probed at our kinematics, constraints on the final states available to the neutron pair can suppress the reaction. This suppression is the origin of the negative value of the pion excesses which have been predicted for pion momenta near 1 fm^{-1}. The forward-angle suppression of electroproduction indicated in our results, particularly at W=1160 MeV may provide the first experimental indications for a significant change in the pion content of nucleons bound in nuclei. The suppression at W=1232 MeV arises in large measure from Fermi broadening because of the proximity to the position of the peak of the delta in the proton, in contrast to the case of W=1160 MeV where such broadening is small.

Our data provide strong evidence that, even in the weakly-bound deuteron, multinucleon processes alter the electroproduction amplitudes in the forward direction.

h. A Study of Longitudinal Charged-Pion Electroproduction in D^2, ^3He, and ^4He (H. E. Jackson, D. F. Geesaman, R. J. Holt, S. Kaufman, E. Kinney, D. Potterveld, B. Zeidman, R. Gilman,* J. Mougey,† B. Saghai,‡ and R. E. Segel§)

Recent studies of pion electroproduction on the deuteron carried out at ALS, Saclay, show that even in the weakly-bound deuteron, multinucleon processes alter the electroproduction amplitudes in the forward direction. The data provide the first experimental indications for a significant change in the pion content of nucleons bound in nuclei. It is clear that a systematic study of forward-angle electroproduction will be necessary to establish quantitatively the sensitivity to the pion content. Rosenbluth separations will be needed to isolate the longitudinal cross section in which pionic charge effects are expected to be most prominent. Measurements for a number of light nuclei will provide useful data on the sensitivity of longitudinal electroproduction to nuclear binding effects. We have submitted a proposal to carry out such a series of measurements at CEBAF using the coincident-pair spectrometer system planned for Hall C. Pions will be observed in the short-orbit spectrometer which will serve as the second arm, and which the ANL medium-energy physics group has proposed to construct.

We propose to study longitudinal charged-pion electroproduction (in the excitation region below the delta isobar) along the direction of the momentum transfer where the charge scattering process dominates. Direct comparison of the cross section per nucleon in deuterium and the helium isotopes with the experimental value for the free nucleon will provide estimates of the strength of the nuclear pion field. A Rosenbluth separation of the longitudinal and transverse cross sections will be performed for four-momentum transfer of 2.5 and 10 fm^{-2}. If current conceptions of pion-exchange currents in nuclei are correct, electroproduction will be suppressed at the lower momentum transfer and enhanced at the higher momentum transfer by the nuclear pion excess.

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i. Electroproduction of Kaons and Light Hypernuclei
(D. F. Geesaman, R. J. Holt, H. E. Jackson, S. B. Kaufman, B. Zeidman, R. E. Segel,* R. Gilman,† and K. Baker‡)

Electroproduction of light hypernuclei is a relatively distortion-free method of investigating the fundamental lambda-nucleon interactions that are critical for understanding complex hypernuclei inasmuch as both the electron and K^+ are weakly interacting particles. In order to perform a detailed investigation of the basic hyperon-nucleon interactions, a proposal to study the electroproduction of kaons in deuterium and other light nuclei has been submitted to CEBAF. The proposal requires coincident detection of the emergent e and K^+ in moderate resolution magnetic spectrometers that are able to provide suitable angular resolution over reasonably large solid angles, namely the HMS and SOS magnetic spectrometers proposed for Hall C. In addition to elucidating the kaon-nucleon-hyperon coupling constants, the study will investigate a theoretically predicted cusp near the sigma threshold.

The particular reactions to be studied are $(e,e'K^+)$ reactions on targets of D, ^{3}He, and ^{4}He at incident electron energies near 2 GeV. The residual nuclei will be left in bound or nearly bound states. The short path length for particles traversing the SOS spectrometer is vital for maintaining reasonable count rates for the detection of the kaons. The reactions proposed provide fundamental information upon which future studies of hypernuclear structure in complex nuclei may be based.

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j. The A-Dependence of the (e,e'p) Reaction in the Quasifree Region

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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 the macroscopic attenuation of 170 ± 30-MeV protons in the nucleus by studying the A-dependence of the (e,e'p) reaction.

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 yields to that predicted by a Plane-Wave Impulse-Approximation calculation. The A dependence of the resulting transmissions is fit with a classical calculation. With a density-dependent nucleon-nucleon effective cross section, the average nuclear matter attenuation length is about 5 fm. Quantum-mechanical Distorted-Wave Impulse-Approximation calculations require optical potentials with similar attenuation lengths. These attenuation lengths are much larger than the simple nuclear matter value of ~2 fm often used to estimate proton attenuation effects.

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At missing energies in excess of 80 MeV, many-body contributions such as multiple scattering and two-body currents appear significant. Attempts to provide a consistent description of the low missing energy (one-body) and high missing energy (many-body) regimes are in progress.

k. 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‡)

In the past year data obtained at LAMPF for positive pion absorption by ^{3}He at 350- and 500-MeV pion kinetic energies have been published. The analysis for both π^+ and π^- absorption at 165 MeV has been completed and a paper is under preparation. The absorption cross section is split into a two-body component, where two nucleons are back to back, and a three-body component, where they share the total energy uniformly within three-body phase space. At 165 MeV the two-body cross section is (16.4±1.5) mb, 1.5 times the cross section for absorption on the deuteron at this pion energy, about twice the value at 62 MeV and 8 times the value at 350 MeV. For π^- at 165 MeV absorbing on the pp pair the cross section is (0.92±0.20) mb, and shows little change over the 62 - 350-MeV region. The three-body cross sections are (9.2±2.0) and (4.2±1.2) mb, respectively. The data at 250 MeV are being analyzed.

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

A number of design options for the high-momentum spectrometer, HMS, in Hall C at CEBAF, were investigated and a QQQD design (3 quadrupoles and 1 dipole) has been determined to be optimal on both scientific and budgetary bases.

The technology chosen for the quadrupoles involves use of superconducting coils with fields shaped by cold iron to minimize external dimensions relative to the apertures. A similar technology will be used for the dipole where, however, the iron is not within the cryo-vessel. Preliminary field and engineering studies have verified the feasibility of the design concepts.
The HMS spectrometer has been reviewed favorably by a Technical Advisory Panel and a DOE committee. A detailed discussion appears in the CEBAF Conceptual Design Report for experimental areas. Since construction of the HMS is primarily an internal responsibility of CEBAF, the ANL effort will be substantially reduced. Except for specific design problems that may arise, the primary interaction will consist of ongoing evaluations and monitoring of engineering efforts.

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

An examination of the proposed experimental program for Hall C at CEBAF reveals a major emphasis on coincidence experiments involving a "core" spectrometer and a second arm capable of detecting particles with momenta <2 GeV/c with moderate energy and angular resolution. In most cases, the core spectrometer serves to tag a virtual photon, which induces a reaction in a nuclear target resulting in the ejection of a hadron in the energy range (0.2-2.0 GeV) which is observed in the second spectrometer. Nuclear physics topics addressed in these experiments include color transparency, nucleon propagation, pion electroproduction, and hyperon physics. All of these programs require an acceptance in the hadron spectrometer as large as possible in solid angle and momentum to maximize operational efficiency. In addition, relatively short spectrometer drift lengths are required in experiments involving detection of pions or kaons in order to minimize decay losses. Because the requirements for energy resolution in this class of experiments is moderate, typically $\sim 10^{-3}$, an optimized design with a short optical length less than 10 m will provide a well-matched spectrometer capability. Excellent particle discrimination will be essential for detection of pions and kaons in the presence of high background fields. Operation at luminosities as high as $10^{38}/cm^2$ sec frequently will be required. To provide this second arm capability we propose the construction of a short-orbit spectrometer, the SOS, based on a $QD\bar{D}$ design which has been developed recently at the Los Alamos Meson Physics Facility. The $QD\bar{D}$ configuration provides a large momentum acceptance, with good energy resolution and solid-angle acceptance in a very compact geometry which can meet the needs of a broad spectrum of studies appropriate for Hall C at CEBAF.

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. A schematic of the spectrometer as it would be constructed at CEBAF is shown in Fig. III-4.

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.

ANL-P-19,928

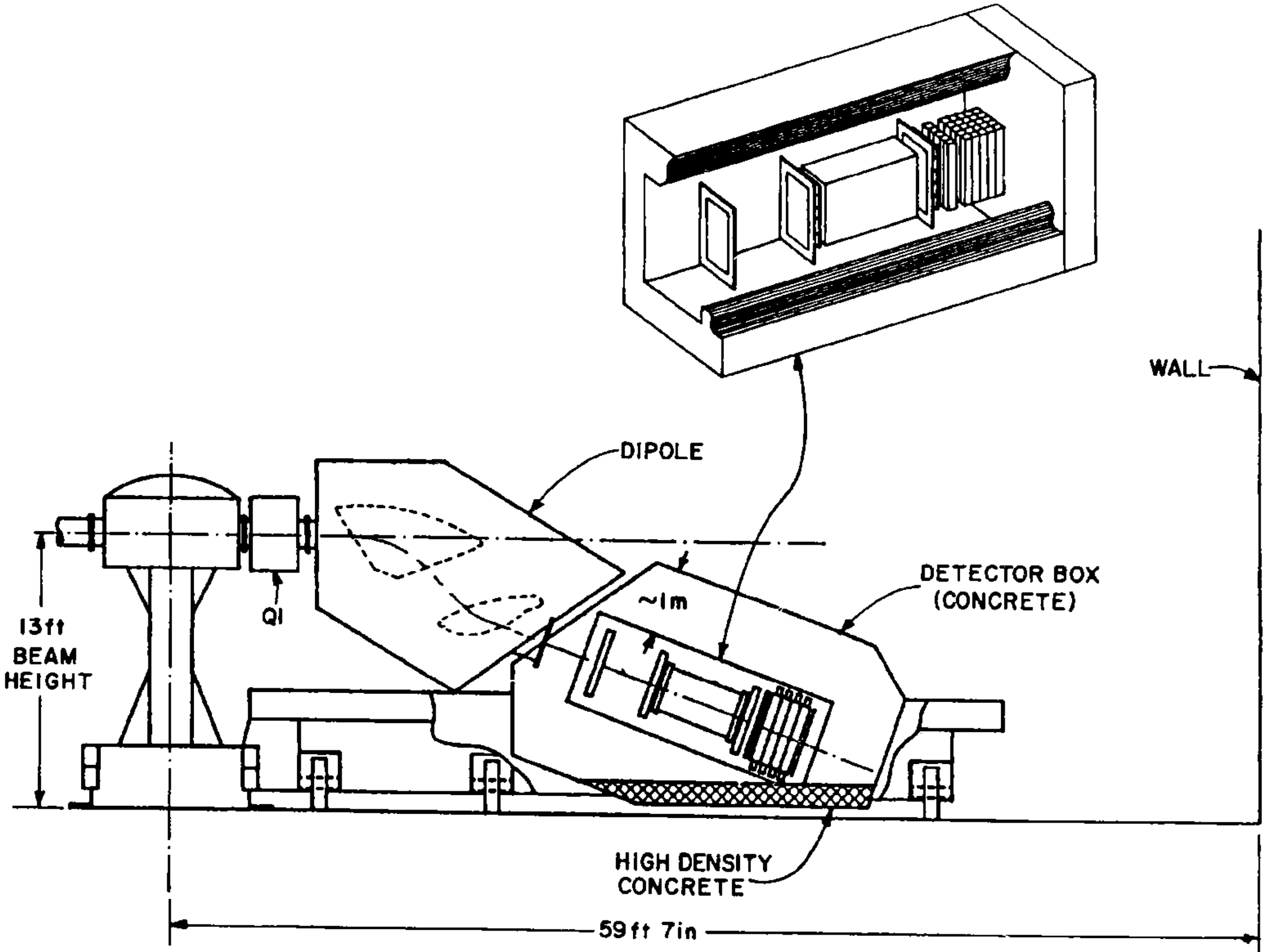

Fig. III-4. Schematic of the proposed CEBAF short-orbit spectrometer. The detector package shown at the upper right consists of two wire chambers, followed by a segmented scintillator, a threshold gas Cerenkov counter, a third wire chamber, a second segmented scintillator, and a lead glass shower array.

n. The Energy Dependence of Nucleon Propagation in Nuclei as Measured in the (e,e'p) Reaction (D. F. Geesaman, R. J. Holt, H. E. Jackson, S. Kaufman, E. Kinney, D. Potterveld, J. P. Schiffer, B. Zeidman, R. E. Segel,* B. W. Filippone,† R. D. McKeown,† R. Milner,‡ and R. Gilman§)

A proposal was presented to the CEBAF PAC-4 to continue the (e,e'p) studies of proton propagation in nuclei for protons in the energy range of 400-2000 MeV. In this energy range the nature of the N-N interaction changes from elastic to highly inelastic once the pion-production threshold is crossed. The theoretical description of proton propagation also changes considerably from nonrelativistic optical potentials to relativistic potentials to Glauber models. Information on proton propagation in this energy range is quite important to the CEBAF coincidence program. Additionally at the highest energies, manifestations of more exotic mechanisms, such as increased transparency for hard collisions, "color transparency", may become evident.

The experiment would be carried out in the CEBAF Hall C using the HMS 6-GeV spectrometer and the SOS 1.8-GeV spectrometer. Electrons in the quasifree region will be detected in coincidence with protons with missing energies of less than 100 MeV. At one proton energy, T_p = 400 MeV, a Rosenbluth separation will be performed to study the A dependence of the longitudinal and transverse coincidence response independently. Since this proposal concentrates on the quasifree region, the projected count rates are relatively high and the background rates are calculated to be quite low, making this an attractive early coincidence experiment for CEBAF.

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o. <u>Studies of Particle Production at Extreme Baryon Densities Produced in Collisions with ^{16}O and ^{28}Si Beams at 14.6 GeV/A</u> (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 relativistic heavy ions with nuclear targets is being studied at the BNL AGS, with the ultimate goal to search for evidence for the formation of a quark-gluon plasma. The present experiment has the immediate goal of understanding the general aspects of relativistic nucleus-nucleus collisions by measuring semi-inclusive spectra of pions, kaons, protons and deuterons produced by interactions of beams of protons, ^{16}O, and ^{28}Si with different targets. In addition, measurements of the transverse energy flow, the longitudinal energy, and the charged-particle multiplicity associated with each event allow the characterization of the event as "central" or "peripheral". The experimental arrangement consists of a magnetic spectrometer with particle identification, and several detectors for the event characterization: a target-multiplicity array, a lead-glass array to measure transverse neutral energy, and a zero-degree calorimeter. Data have been taken for targets of Aℓ, Cu, Ag, and Au, for an angular range of 5° to 55°.

Initial measurements of this experiment have shown that there is complete stopping of an ^{16}O projectile in a nucleus as light as Cu, in agreement with the expectation that these reactions would produce systems of high baryon density and high energy density. The most interesting result has been the observation of enhanced cross sections for producing K^+ mesons with heavy-ion beams as compared to proton beams. It has been suggested that enhanced strange-particle production may be a signature of the formation of a quark-

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gluon plasma in the collision. Whether our data demonstrate this effect or whether the large K^+/π^+ ratio arises from some more mundane aspect of the reaction, such as rescattering, requires further experimental measurements. The momentum spectra of the different particles are all consistent with an exponential dependence on the transverse mass ($mt = [pt^2 + m^2]^{1/2}$), as expected for emission from a hot thermal system.

Correlations between identical particles are also being studied to give information on the spatial and temporal extent of the particle production region (Hanbury-Brown, Twiss effect). The preliminary results indicate that the spatial radius of the production zone is ~4-5 fm, similar to the results obtained at CERN energies.

The group at Argonne has participated in the experiment in a number of ways, as the interests of the members and the needs of the experiment have changed. We coordinated how the electronic signals from the different detectors were brought into correct timing for the on-line trigger, and worked on the design and implementation of a generalized trigger supervisor. We participated in the calibration and running of the zero-degree calorimeter, as well as in the analysis of the resulting data. We also have been analyzing the data from the target-multiplicity array, and have done Monte Carlo simulations of the response of this array to determine its acceptances for different angular and momentum ranges. A second-generation experiment will have its first run in May-June 1990.

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

(S. B. Kaufman, F. Videbaek, T. Blaich,† H. C. Britt,* Y. D. Chan,‡,
A. Dacal,‡ D. J. Fields,*, M. M. Fowler,† Z. Fraenkel,§
L. F. Hansen,* A. Harmon,‡ R. G. Lanier,* M. N. Namboodiri,*
J. Pouliot,‡ B. Remington,* T. C. Sangster,* R. Stokstad,‡
G. Struble,* M. Webb,* and J. Wilhelmy†)

A systematic study of heavy-ion nuclear reaction mechanisms at intermediate energies (50-100 MeV/A) was done at the LBL Bevalac. The objectives of this experiment were to investigate the transition from the collective phenomena observed at lower energies and the nucleon-nucleon interaction region at relativistic energies. Beams of Nb ions with energies of 50, 75, and 100 MeV/A were used to bombard a Au target, and the energies and angles of the emitted fragments were measured. A forward-angle 34-element hodoscope detected projectile-like fragments, eight gas telescopes measured medium- and heavy-mass fragments, and scintillator phoswiches detected energetic light charged particles. The major observations were: the reaction yields are similar over the projectile energy range; central collisions have a high multiplicity of intermediate-mass fragments with broad angular correlations; and binary fission is observed for the more peripheral collisions. Data analysis for this experiment is being done primarily at Los Alamos and Livermore Laboratories.

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B. 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 final year of production-data running for the neutrino oscillations was completed during three LAMPF beam cycles in 1989. The three-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 last year. The measured lifetime is consistent with the previously-measured neutron asymmetry parameters. An improved lifetime measurement was performed in 1989 and data analysis is nearing completion. A new experiment to test time-reversal invariance in neutron decay is now being developed. This experiment will use large-area silicon detectors to detect recoil protons and electrons.

The first stage of an experiment to better determine the Cabibbo angle by measuring the partial lifetime from the superallowed decay of ^{10}C has been completed. A new technique was developed, allowing 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. The experimental work is continuing with the aim of further improving the precision.

An experiment to help determine the rate of solar Hep neutrino production was completed at ILL, and the results were published.

Other experiments to pin down low-energy cross sections of astrophysical interest continue at the new ATLAS ECR source.

A new experiment which utilizes the technique of laser trapping of neutral atoms has begun this year. The intention is to trap and polarize radioactive ^{21}Na allowing a precise measurement of the beta-decay asymmetry. This work is complementary to ongoing experiments to study other mirror systems which employ polarized light-ion beams to make the radioactive species. The new laser-trapping technique should allow us to set better limits on right-handed currents in the weak interaction.

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

Experiment E-645 is a search for $\bar{\nu}_e$'s produced in the LAMPF beamstop. The beamstop is a copious source of ν_μ, $\bar{\nu}_\mu$, and ν_e but not of $\bar{\nu}_e$, so a signal would suggest the transformation of a produced neutrino into $\bar{\nu}_e$. Our experiment employs a 20-ton target/tracking-detector consisting of 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 2000 g/cm^2 of overburden, about 26 meters from the LAMPF beamstop. The detection method is by inverse beta decay on the proton and the experimental signal is the track of final-state positron (maximum energy 52.8 MeV) required to have the correct dE/dx and the corresponding range. In addition, the scintillator counter layers are covered with thin sheets of gadolinium, allowing us to identify the neutron in the final state by delayed-capture gamma-ray signals in the scintillators.

The detector was exposed to the beamstop neutrino source for three full LAMPF operating years in 1987, 1988 and 1989. The 1987 data were analyzed previously and without using neutron detection and we were able to rule out an interesting range of neutrino oscillation parameters. Our conclusions were published last year. These initial limits contradicted positive neutrino oscillations that were then being reported from experiments at CERN and BNL.

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Data taking was completed in 1989 and the analysis of the entire three-year data set is now being completed. The data are being analyzed for neutrino oscillation signals that might come from neutrinos produced by stopped pions and muons, and also from neutrinos coming from the in-flight decay of pions. The data should also provide limits on the unexpected decay, $\pi^0 \rightarrow \nu\bar{\nu}$, as well as other possible exotic processes.

The final analysis will be completed in 1990. The ANL cosmic-ray shield is now being used in conjunction with the Cygnus airshower array.

b. Search for Cosmic-Ray Point Sources (S. J. Freedman, B. K. Fujikawa, D. A. Krakauer, J. Last, J. E. Nelson, and the Los Alamos Cygnus collaboration: University of Maryland, University of California-Irvine, and Los Alamos National Laboratory)

At the conclusion of data taking for E-645 the cosmic-ray shield was incorporated into the Cygnus airshower array on a full-time basis. The shield is used as an underground muon detector and it more than doubles the muon detection area of Cygnus. Some improvements in the data-acquisition system will be made in the next few months and then the shield will become a permanent component of the array.

We have nearly completed our development of an inexpensive cosmic-ray detector that could be used in an expanded array at Los Alamos. A paper describing the performance of four liquid-scintillator counters built by us is being prepared for publication. Three of the detectors are constructed of ordinary steel drums (55, 85, and 110 gallons) and the fourth is made of a 2-m high .7-m diameter PVC tank. Each detector contains a layer of liquid scintillator at the bottom viewed with a single photomultiplier at the top. The four prototypes will be operated outside at Argonne this winter.

c. A Measurement of the Neutron Lifetime (S. J. Freedman, J. Last, H. Abele,* J. Doehner,* H. Borel,* I Reichert,* G. Zwenger,* and D. Dubbers†)

An improved version of our previous neutron lifetime experiment, using a chopped beam of neutrons, was run for two 40-day reactor cycles in 1989. The experimental method avoids systematic effects associated with measuring the absolute beta decay rate. With a chopped beam, entire pulses can be contained in the 2-m-long PERKEO spectrometer during counting, and it is not necessary to know the exact geometry or the neutron velocity spectrum. The absolute neutron flux is measured by irradiating thick samples of cobalt powder. The result of the first run of this experiment (τ=876±21 sec) was published. The most significant systematic uncertainty from detector drift was eliminated in the latest experiment by an elaborate stabilization system. Along with other improvements and longer data-collection times we expect a significantly improved precision. The data analysis is now being completed and we expect to publish our new neutron lifetime value in 1990.

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

The most precise value of the weak vector coupling constant G_V now comes from $0^+ \to 0^+$ superallowed nuclear beta decay. In principle the best experiment in a nuclear system is the decay of ^{10}C because it is relatively insensitive to radiative corrections. Unfortunately the experimental uncertainty in the branching ratio to the 0^+ excited state of ^{10}B is large and the best determinations are from higher-Z systems. We are remeasuring this branching ratio using the EN tandem of Western Michigan University in Kalamazoo. An enriched ^{10}B target is bombarded with 8-MeV protons to produce ^{10}C. The experiment determines the branching ratio from observations of the cascade γ rays with Ge-detectors following beta decay. The crucial γ-ray efficiency calibration is done in beam with the $^{10}B(p,p')^{10}B^*$ reaction to excite the 0^+ state. By measuring γ rays in coincidence with back-scattered protons of the right energy, the necessary relative calibration is accomplished in exactly the same geometry as the decay measurement.

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The experimental technique was refined in 1988 and 1989 and production running was completed at the Western Michigan University Tandem. The combined statistical and systematic error of these measurements is below 1.0%. The final data analysis is nearly complete. We will publish our present result in 1990 before proceeding with the next phase of the experiment to reduce the error further.

e. The Decay of Polarized Mirror Nuclei (K. P. Coulter, B. K. Fujikawa, S. J. Freedman, D. A. Krakauer, J. E. Nelson, Z. Lu,* and C. A. Gossett†)

The measurement of beta asymmetry parameters in selected nuclear systems is sensitive to many important properties of the weak interaction. In particular cases the beta asymmetry is affected by possible and expected induced currents and by the strength of the fundamental vector coupling constant. We continue to apply the method of polarizing radioactive nuclei in reactions with polarized projectiles in order to study these effects. These experiments will utilize polarized light-ion beams from the University of Washington Tandem Laboratory.

An apparatus to measure the beta asymmetry in selected mirror systems is now completed at Argonne. The detector incorporates a large NaI(Tℓ) detector and two novel 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 ≈ 1.5 Kgauss. The absolute size of the ground-state beta asymmetry for mirror systems that also have a pure Gamow-Teller transition to an excited state of the daughter will be measured with this system. The excited-state decays are 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 uniquely predicted by the spins involved. With the polarization measured we can determined the ground-state-to-ground-state asymmetry. Combined with measurements of the beta-decay lifetime these measurements can be used to determined G_V for these transitions. Measurements of G_V in mirror decay have previously been made for the neutron, ^{19}Ne, and ^{35}Ar and we hope to extend these measurements to other mirror nuclei.

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f. <u>Measurement of the $D(D,\gamma)^4He$ Reaction at the ATLAS ECR Ion Source</u>

(K. P. Coulter, P. Fernandez, S. J. Freedman, D. A. Krakauer, J. Last, R. Pardo, F. L. H. Wolfs, J. Gehring,* and T. F. Wang†)

The $D(D,\gamma)^4He$ cross section at extremely low energies is experimental input 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 ^4He 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 the $D(D,\gamma)^4He$ at deuteron energies down to 50 keV using a pulsed beam of deuterons from the new ATLAS Electron Cyclotron Resonance ion (ECR) source. The pulsed beam combined with a time-of-flight gamma-ray detection 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 also be useful in other low-energy cross-section measurements of astrophysical interest.

The first low beam-intensity test runs of the experiment were completed this year. We measured the beam-pulsing properties and observed gamma rays from the capture of protons on ^{11}B. Figure III-5 presents typical data, and demonstrates the 20:1 signal-to-noise improvement enabled by the ECR timing properties. It was clear from these tests and from our first attempts to observe $D(D,\gamma)^4He$ that we need to effectively utilize the high beam intensity available from the ECR. It will be necessary to improve the efficiency of the beam transport system before continuing with the experiment. After the beam-line improvements we will complete tests of the setup and proceed with the measurement.

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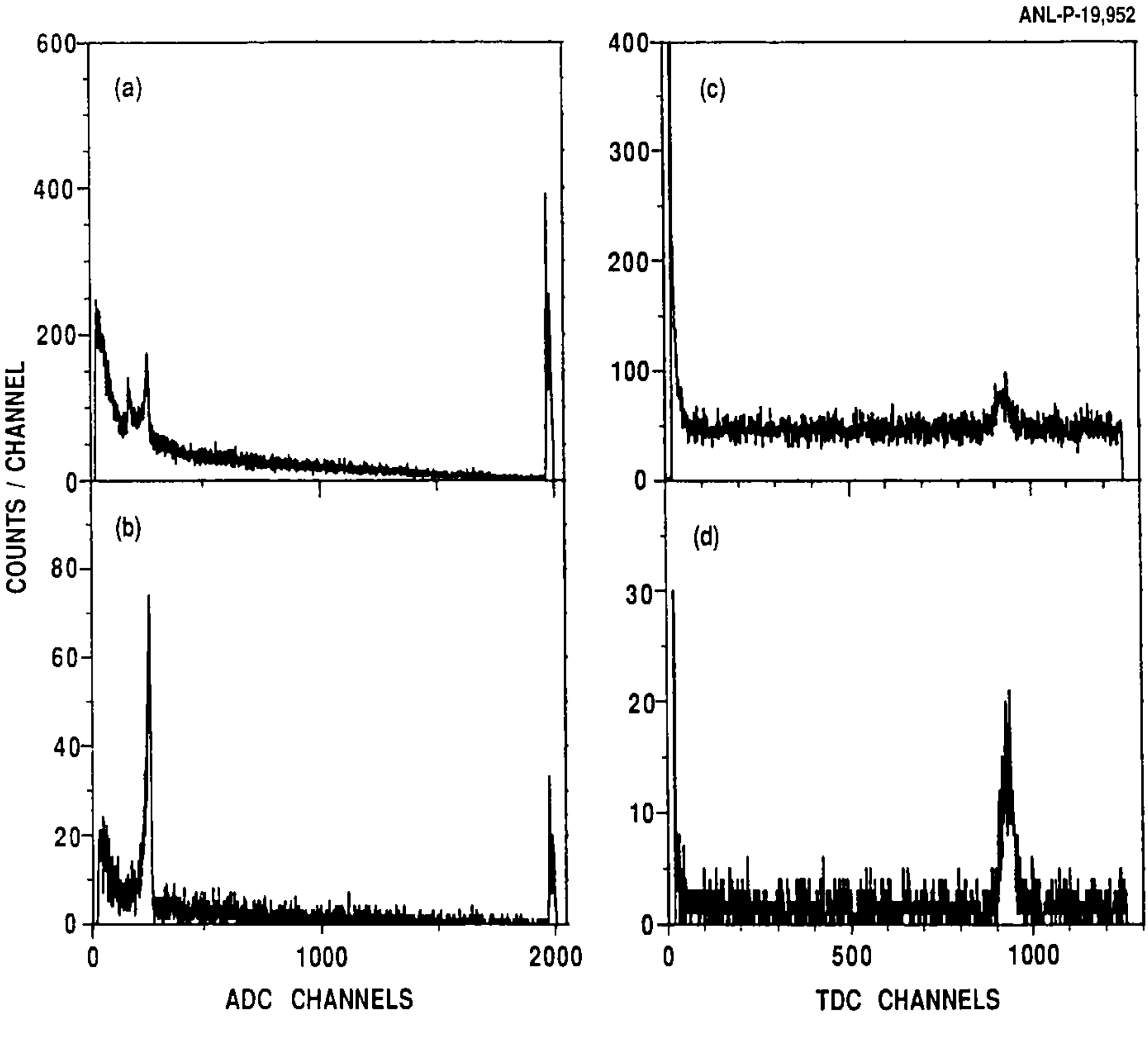

Fig. III-5. Signal-to-noise improvements using pulsed-beam timing characteristics of the ECR source. a) NaI energy spectrum for $^{11}B(p,\gamma)$; b) NaI timing spectrum; c) NaI energy spectrum gated on timing peak; d) NaI timing for NaI energy peak.

g. Measurement of the $^3He(n,\gamma)^4He$ Cross Section at Thermal Neutron Energies

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

The highest energy neutrinos produced in the sun, with energies up to 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.

The principal limit in knowing the Hep neutrino flux is the uncertainty in the $^3He(p,e^+\nu)^4He$ reaction cross section (which is too small to be measured directly in the laboratory). However, this cross section is simply related to the s-wave $^3He(n,\gamma)^4He$ cross-section for very low-energy neutrons. The experimental value for the neutron capture cross section was obtained in three previous experiments; two are consistent with $\sigma = 60$ μb (20% errors), while one implies $\sigma = 29\pm9$ μb, and disagrees.

We measured the capture cross section in a run at Grenoble during September and October 1988, with the aim of reducing the uncertainty in the $^3He(n,\gamma)^4He$ cross section and resolving the significant discrepancy between the previous experiments. 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 ^{14}N capture cross section. The measured cross section for $^3He(n,\gamma)^4He$ is 54±6 μb. The astrophysical S-factor for $^3He(p,e^+\nu)^4He$ obtained from the measured cross section for $^3He(n,\gamma)^4He$ is calculated to be $(15.3\pm4.7)\times10^{-20}$ keV-b. The corresponding flux of Hep neutrinos predicted by the standard solar model is 1.5×10^4 $cm^{-2}s^{-1}$. The number of Hep-induced events in the proposed Sudbury Neutrino Observatory should be 94 per year (above 5 MeV). The results of this measurement have been published.

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

In the course of high-precision experiments with low-energy neutrons we have searched for convenient materials which absorb neutrons without producing background γ rays. One common material for this purpose is ^6LiF but in its usual form it is difficult to use as a coating. We have devised a simple method of painting surfaces with a special compound containing ^6LiF which, after heat treatment, produces a hard durable surface containing only small 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 have tested various compounds containing ^6Li at the reactor facilities at the National Institute of Standards and Technology at Gaithersburg. We have measured the background produced by our new shielding material before and after heat treatment. Of particular interest is the background produced by neutron capture on hydrogen in the material, which produces 2.2-MeV γ rays. As comparison, we have also determined the γ-ray background produced by ^6LiPb. These measurements show that our new shielding material produces a background rate of 2.2-MeV γ rays at least 10 times as low as that produced by ^6LiPb. In addition, we have shown that the heat treatment reduces the background rate by another factor of 4. A measurement of the total neutron absorption rate in our compound shows that the ^6LiF is distributed very homogeneously.

We plan to continue our measurements in 1990, and want to determine the background rate as function of the specifics of the heat treatment (temperature and length). In addition, we want to determine the maximum concentration of ^6LiF in our compound. We plan to submit the results of our work for publication.

i. <u>A New Measurement of Possible Time-Reversal Non-Invariant Correlations in Neutron β-Decay</u> (S. J. Freedman, B. K. Fujikawa, D. A. Krakauer, J. Last, J. E. Nelson, and F. L. H. Wolfs)

The decay probability for polarized neutrons is expected to contain a correlation of the form, $D\overline{J}\times\overline{p}_e\cdot\overline{p}_\nu$. 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 $\approx 2\times10^{-5}$. A significantly different value of D could signal time symmetry non-invariance. 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 neutron beam intensities and polarizations polarizations obtained over the years at the ILL. A large-area detector with high efficiency for low-energy protons is critical to our method. We are presently developing a large-area silicon detector that will be used to detect both electrons and protons.

A silicon detector test facility has been set up at the BLASE low-energy accelerator at Argonne. A low-energy (20- to 200-keV) beam is scattered from a thin gold foil. The scattered beam, at 90°, is used to study the response of various silicon detectors to protons.

j. <u>Investigation of "Cold Fusion"</u> (S. J. Freedman, D. A. Krakauer, J. Last, J. E. Nelson and F. L. H. Wolfs)

We conducted several experimental searches for cold nuclear fusion using a variety of detectors. We observed no positive evidence for nuclear fusion. The most extensive tests employed a large (10" X 12") NaI detector to search for neutron-capture gamma rays in delayed coincidence with recoil protons in a large plastic scintillator. We found no evidence of excess neutron production from either electrolytic cells or from deuterium-gas-loaded Ti shavings in several weeks of running.

In another experiment with S. Zaromb of the BEM Division at ANL, we searched for proton or alpha production in a small electrolytic cell. A sensitive Si surface-barrier detector was used to detect charged particles emerging from a thin Ti electrode. There were no counts beyond that expected from cosmic-ray interactions (a few per hour) even when Li loading and electric current were increased substantially.

Finally, we have noted that the only remaining evidence for cold fusion (Jones et al.) contains a curious systematic correlation between the strength of the signal and the statistical error bars. This correlation could indicate that there was a systematic bias in the data-collection procedure. We have submitted a comment for publication.

k. Liquid Scintillation Detector Development and the BOREX Solar-Neutrino Experiment (S. J. Freedman, B. K. Fujikawa, J. Last, D. A. Krakauer, J. E. Nelson, R. Konopka, and M. Natsis)

We have been pursuing a recently developed idea that tracking and particle identification can be improved in large liquid-scintillation detectors by observing Cerenkov radiation. The ability to observe both scintillation and Cerenkov light may enable a large detector to achieve the low-energy threshold allowed by scintillation detectors while incorporating the improved track-angle resolution and particle discrimination possible with imaging Cerenkov detectors.

We have constructed a small test tank to observe Cerenkov radiation in mineral oil and dilute liquid scintillator and thereby characterize the light emission characteristics of these detection media. In parallel with this experimental effort we have obtained codes from the Sudbury Neutrino Observatory for Monte Carlo simulation of imaging Cerenkov detectors. These codes have been modified to include weak scintillation light.

We continue to maintain interest in the BOREX proposal for a large liquid scintillator solar-neutrino detector and intend to determine how the Cerenkov imaging capabilities may improve that detector. A BOREX group meeting is scheduled for this international collaboration to be held at ANL in February 1990.

ℓ. LASER Trapping of Radioactive Atoms (K. P. Coulter, B. K. Fujikawa, S. J. Freedman, D. A. Krakauer, J. E. Nelson, L. Young, Z. Lu,* C. E. Wieman,† and T. G. Walker†)

Recent advances have demonstrated that large numbers of neutral atoms from a diffuse, thermal source may be easily trapped with standard laser techniques. Up to now investigations have concentrated on the physical processes of the traps themselves, and on simplifying techniques for loading the traps. As these techniques develop, the exploitation of these phenomena present exciting opportunities in other areas of research.

Our group has begun to set up a facility in the Physics Division with which to study and gain experience with the atom-trapping technique. We will then apply this experience to trap radioactive sodium atoms, the first such application of this technique. The trapped ^{21}Na atoms will be a radioactive source for a precision measurement of beta-decay asymmetry, similar in principle to the experiment to detect the decay of polarized mirror nuclei described above. The physics of the atom trap allows the measurement to be made with very low background, small systematic effects, and a large and well-known nuclear polarization. These efforts make use of other laser facilities and expertise presently in the Division's atomic physics group and the Joint Institute for Laboratory Astrophysics as well as the expertise in precision measurement of our own weak interactions group.

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IV. THEORETICAL NUCLEAR PHYSICS

The main effort of the theory group is devoted to the investigation of nuclear dynamics and the related fundamental theoretical problems. We have developed Hamiltonian models for describing the hadronic and the electromagnetic excitations of subnucleon degrees of freedom in terms of the mechanisms deduced from effective Lagrangian field theories and hadron models inspired by quantum chromodynamics (QCD). The light-front-dynamics formulation has been used to investigate the electromagnetic form factors and the spin function of the nucleon within the constituent quark model, and to investigate deep inelastic lepton scattering by three-nucleon systems. We have extended the variational Monte-Carlo method to calculate the ground-state properties of six-nucleon systems and of ^{16}O using a cluster-expansion approach, and to investigate electroweak reactions on light nuclei which are of astrophysical interest. A unified coupled-channel model has been developed to describe heavy-ion elastic scattering, inelastic scattering, nucleon-transfer and fusion processes in terms of a limited number of nuclear parameters. The superdeformed states in the Hg region have been correctly predicted by our cranked Strutinsky calculation.

We stress the importance of developing reliable approximations for calculating the dynamical consequences of the models we proposed. We also emphasize extensive confrontations with experimental data. The group has very extensive collaborations with theory groups at universities and other research institutes, and interacts strongly with experimental groups at Argonne and other laboratories.

A. NUCLEAR DYNAMICS WITH SUBNUCLEON DEGREES OF FREEDOM

(A. Bodmer, F. Coester, P. L. Chung, T.-S. H. Lee, S. C. Pieper, C. Roberts, R. Wiringa, and Others)

The focus of our program is the development of theoretical models for describing nuclear dynamics in the kinematic regions where the subnucleon degrees of freedom become explicit and/or relativistic effects are important. Our work has two major parts which are complementary to each other. The first part is the construction of a model Hamiltonian with the assumption that the relevant degrees of freedom of a nuclear system are the nucleon, the pion, and the Δ. We further assume that the basic interaction mechanisms at large distances can be deduced from an effective Lagrangian field theory. The interactions at short distances are calculated from or parameterized according to current understanding of the hadron structure and the multi-quark dynamics. Such a model Hamiltonian has been constructed from our previous studies of πN, NN and πd reactions, and is constantly being improved by incorporating new information extracted from QCD studies of hadronic interactions. In FY 1989 and FY 1990 we succeeded in extending the model to include coupling with the electromagnetic field. The model can describe, to a very large extent, the data of electromagnetic production of pions on the nucleon. We have made extensive predictions of the (γ,π) and $(e,e'\pi)$ reactions on the nucleon and the few-nucleon systems, which can be tested in the near future by the experiments at Bates, SLAC, Mainz, Bonn, and CEBAF. To improve the dynamical content of the model, we have started to develop an approach in which the meson form factors calculated from a QCD-inspired non-local Nambu-Jona-Lasinio model are incorporated into our formulation of the problem.

The second part of our work is the development of a fully relativistic approach to investigate the electromagnetic properties of the nucleon and the few-nucleon systems. In a light-front dynamics formulation, we show that the relativistic composition of the quark spins is essential to obtaining a satisfactory description of the electromagnetic form factors of the nucleon within the constituent quark model.

Recent measurements show the spin-structure function of the proton to be much smaller than is predicted by naive quark models. We have shown that Melosh rotations of the quark spins can account for the required reduction. We have also made use of available accurate three-nucleon bound-state wave functions to explore the validity of the convolution model commonly used in describing deep-inelastic lepton scattering by nuclei. The relativistic corrections to the magnetic and quadrupole moments of the deuteron have been calculated and are shown to be negligibly small.

We have developed an approach for investigating the extent to which color transparency, a concept originated from some QCD considerations, can be realized in high-energy (p,2p) reactions.

With the advances we have made recently in calculating the properties of closed-shell nuclei starting with realistic two- and three-nucleon potentials, we have revived our effort in calculating the pion excess in nuclear bound states. We have also continued our investigations of hypernuclei and relativistic mean-field theory of nuclei.

a. Nuclear Hamiltonian with Pion and Delta Degrees of Freedom and Its Coupling With the Electromagnetic Field (T.-S. H. Lee, C. Fasano,* A. Matsuyama,† and others)

To investigate nuclear dynamics at intermediate energies, we had developed in previous years an approach to construct a model Hamiltonian for the nucleon, the pion, and the delta degrees of freedom. The main tasks were to carry out extensive studies of πN, NN and πd scattering. Two models have been developed and well programmed for generating dynamical input to study nuclear dynamics at intermediate energies. The first model is based on an extension of the Paris potential to include the one-pion-exchange coupling to the $N\Delta$ state and its subsequent decay into a πNN channel. This model has been widely used by the intermediate energy physics community in analyzing new pp and np scattering data at LANL and Saclay, and pd reaction data. The second model contains meson-exchange interactions at large distances and a short-range separable parameterization motivated by our quark-compound-bag model study of NN scattering. This QCD-inspired model gives the most precise fit to the recent Arndt phase shifts. Its main success is to resolve the long-standing difficulty in describing the energy-dependence of the pp polarization total cross sections. Some of our results are shown in Fig. IV-1. This work, a part of C. Fasano's Ph.D. thesis (University of Chicago, 1989) has been accepted for publication. With the hadronic part of the model under control, our main effort in FY 1989 and FY 1990 is to extend the model to include the coupling with the electromagnetic field. The resulting model Hamiltonian has now positioned us to explore the physics at Bates, SLAC, Mainz, and Bonn in the near future and at CEBAF eventually. Our accomplishments in this new direction are described in the following four subsections.

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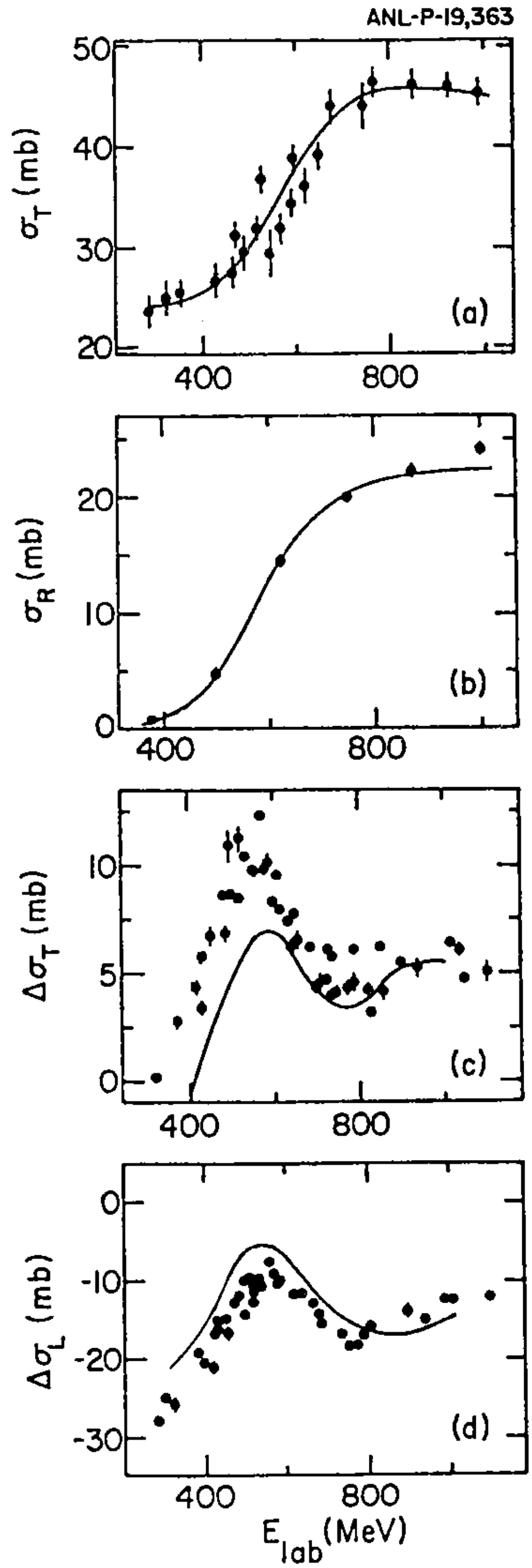

Fig. IV-1. The data are compared with the calculated pp total cross section (σ_T), total reaction cross section (σ_R), transeven-transeven total cross sections $\Delta\sigma_T$, and longitudinal-longitudinal total cross section ($\Delta\sigma_L$).

b. <u>A Dynamical Model of Electromagnetic Production of Pions on the Nucleon</u> (T.-S. H. Lee, B. Blankleider,* and S. Nozawa†)

Pion photoproduction on the nucleon is investigated using a model Hamiltonian defined in the channel space $H=\pi N\oplus\gamma N\oplus B$ with $B=\Delta$ and N. The basic electromagnetic matrix elements are deduced from the low-order Feynman amplitudes calculated from a Lagrangian describing interactions among γ,π,ρ,ω,N and Δ fields. The πN interaction is described by $B\leftrightarrow\pi N$ vertices, and a two-body separable potential. A scattering formalism is introduced to assure that the constructed pion photoproduction amplitude is unitary and gauge invariant. The πN parameters are determined by fitting the phase shift data up to 500-MeV incident pion energy. The remaining three free parameters of the model, Λ, the cutoff for the form factor which regularizes the Born (non-resonant) terms, G_M, and G_E for the $\gamma N\leftrightarrow\Delta$ vertex, are determined by fitting the $M_{1+}(3/2)$ and $E_{1+}(3/2)$ multipole data. The resulting E2/M1 ratio for the $\gamma N\leftrightarrow\Delta$ excitation is -0.035. The model can, to a large extent, describe the existing cross section and polarization data for $\gamma p\rightarrow\pi^+n$, $\gamma p\rightarrow\pi^0p$ and $\gamma n\rightarrow\pi^-p$ up to 400-MeV incident photon energy. The importance of unitarity in extracting the basic parameters from the data is demonstrated explicitly. It is also shown that, within the present unitary model, πN off-shell effects can account for up to 50% of the cross section. For the interpretation of experimental data, this indicates a significant difference between the present Hamiltonian approach and those that use only Watson's theorem to impose unitarity. The model is consistent with the existing unitary πNN models, and hence can be directly applied to studying pion photoproduction on the deuteron and heavier nuclei. A paper describing this work has been accepted for publication. Some of our results are shown in Fig. IV-2.

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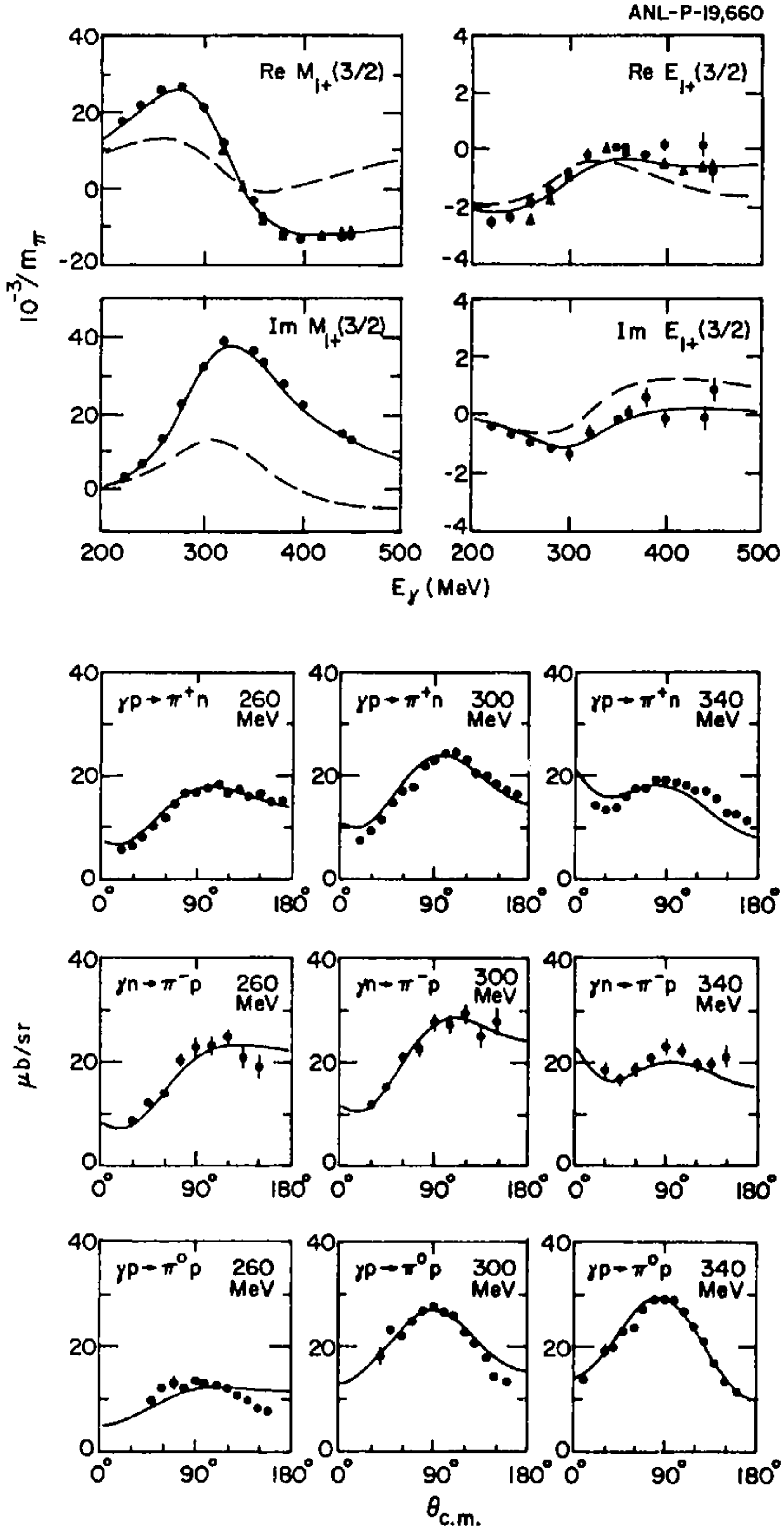

Fig. IV-2. The calculated pion photoproduction amplitudes M_1+ and E_1+, and various differential cross sections are compared with the data.

c. The $\gamma+N\leftrightarrow\Delta$ Electric Quadrupole and Charge Form Factors
(T.-S. H. Lee and S. Nozawa*)

Electroproduction of pions on nucleons is investigated with the dynamical model of Sect. A.b. The predicted cross sections are in good agreement with the inclusive p(e,e') data, and reproduce, to a large extent, the p(e,e'π) triple coincidence data. Some of our results are shown in Fig. IV-3. The model dependence of our predictions is briefly examined by also using the Gross-Riska approach to parameterize the electromagnetic vertices of the Born (non-resonant) term. Various polarization observables of the inclusive $\vec{p}(\vec{e},e')$ and the exclusive $p(\vec{e},e'\pi)$ reactions are also predicted. The extent to which the $\gamma N\leftrightarrow\Delta$ electric-quadrupole and charge form factors can be determined in future experiments has been predicted. This work has been accepted for publication.

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d. Pion-Photoproduction at Threshold and Low-Energy Theorem
(T.-S. H. Lee, S. Nozawa,* and B. Blankleider†)

Neutral pion photoproduction on the nucleon near threshold is investigated using the dynamical model of Sect. A.b. Analytic properties of the final-state interaction amplitude in the energy region near the π^+n production threshold are examined in detail. It is shown that the commonly-used procedure, based on an analytical continuation of the K-matrix to the unphysical region, is not compatible with an approach incorporating full off-energy-shell dynamics. Our calculation indicates that the final-state interaction amplitude derived from a dynamical model, could involve a large cancellation between the different pion-photoproduction mechanisms. This leads to the surprising result that the final-state interaction effect due to the intermediate π^0p state can be as important as that due to the π^+n intermediate state. At threshold, we obtain $E_{0+}=-1.92\times10^{-3}/m_{\pi+}$. This number is close to the measured value of $E_{0+}=-1.5\times10^{-3}/m_{\pi+}$. No violation of the low-energy theorem is required to obtain good agreement between the calculated total cross sections and experimental data from threshold to about 400-MeV incident photon energy. This is in sharp contradiction with the claim based on the K-matrix approach. A paper on this work has been published. Some of our results are shown in Fig. IV-4.

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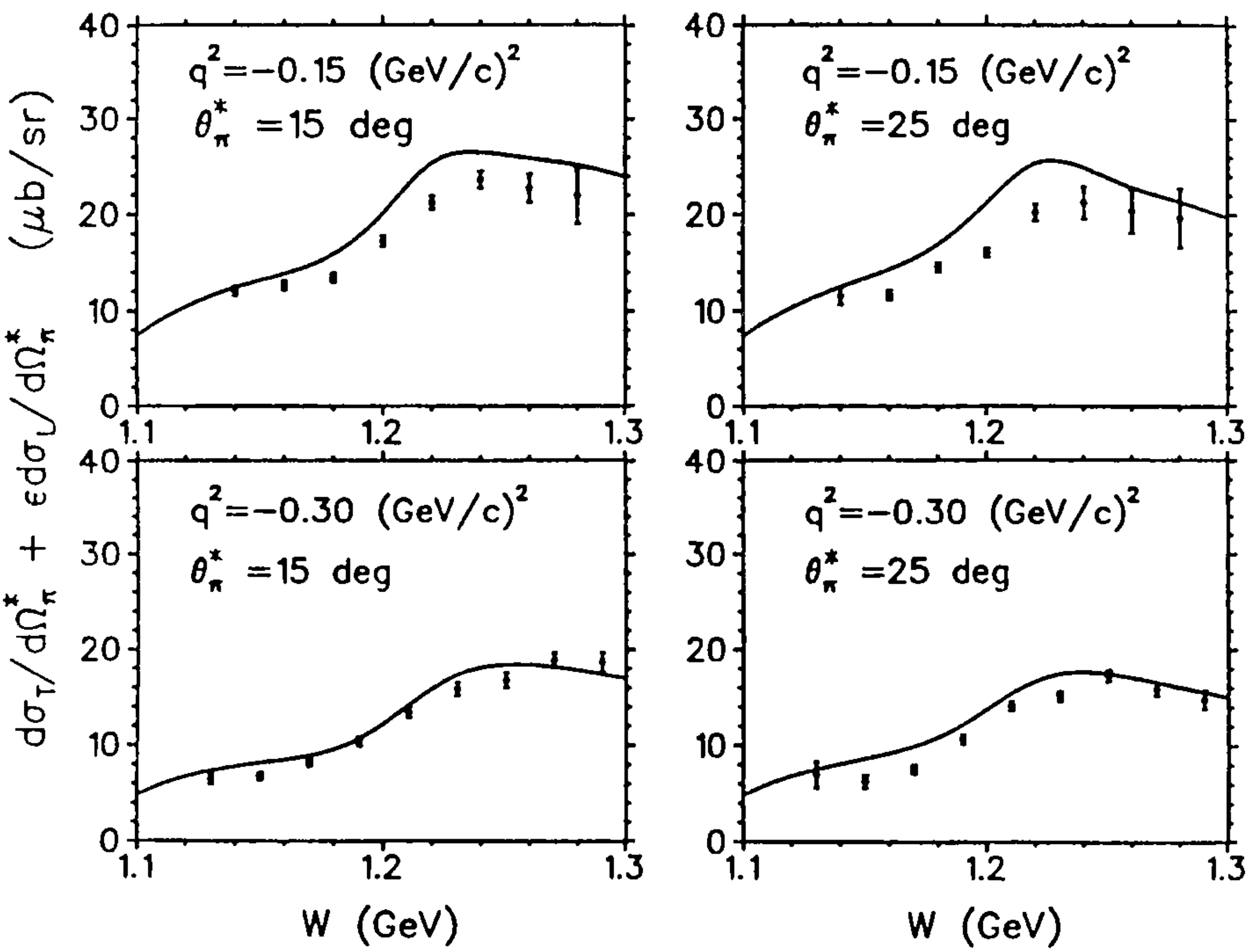

Fig. IV-3. The calculated $p(e,e'\pi^0)$ cross sections are compared with data.

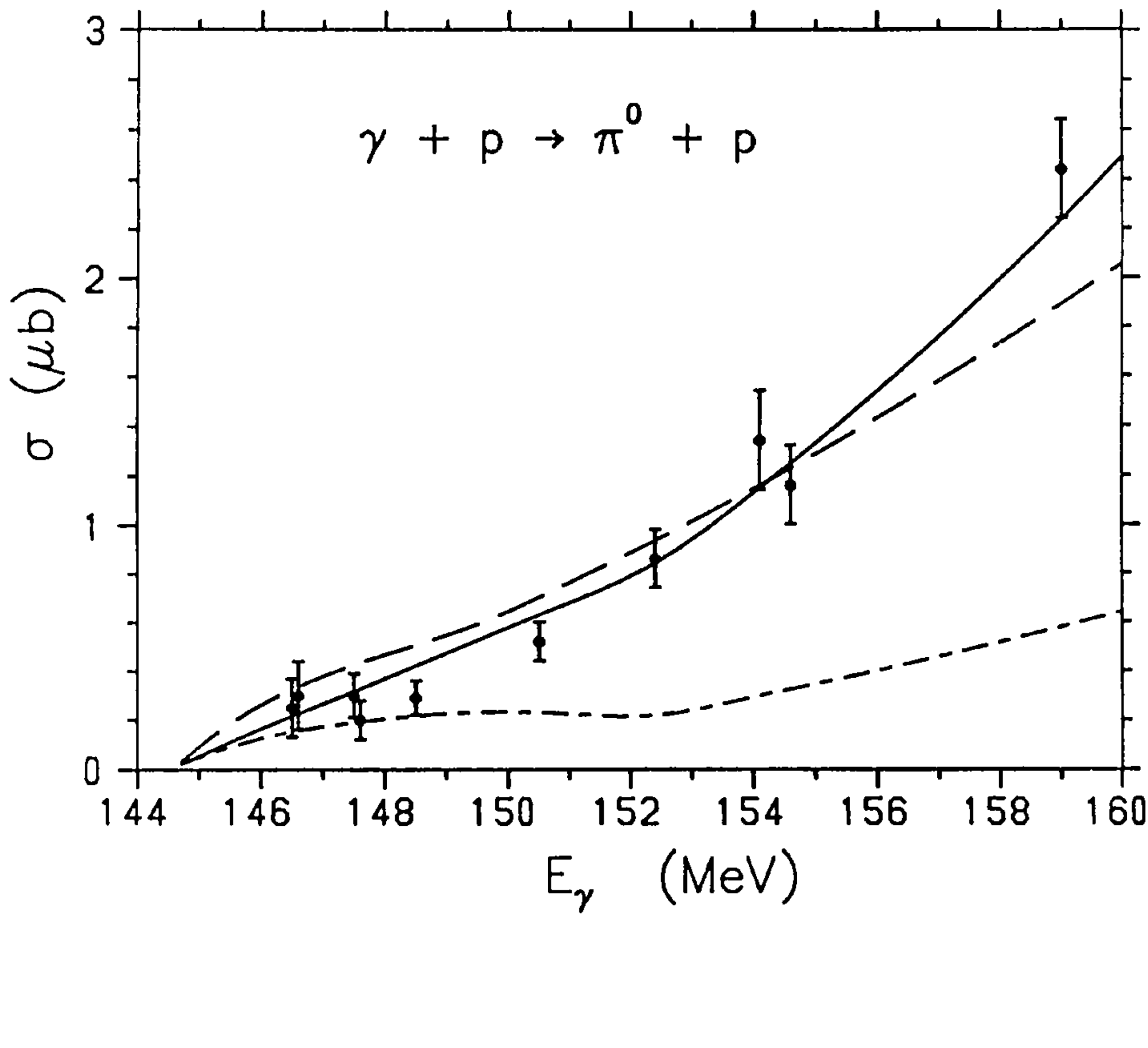

Fig. IV-4. The calculated total cross sections of $\gamma p \rightarrow \pi^0 p$ near threshold are compared with the data. The dashed and dashed-dotted curves are calculated respectively from Born term alone and from E_{0+} amplitude alone.

e. Photodisintegration of the Deuteron (T.-S. H. Lee and H. Tanabe*)

With the Hamiltonian models described in Sects. A.a and A.b, we have investigated the photo-disintegration of the deuteron. It is assumed that a pion is first photo-produced from one of the nucleons in the deuteron, and is subsequently absorbed by the second nucleon. The outgoing two baryons interact with each other via the exchange of mesons. Our results in FY 1988 indicated that such a meson-exchange calculation can not describe the $d(\gamma,p)n$ data in the 1-2 GeV energy region. In FY 1989 we explored the model-dependence of our results. We obtained three major results: (1) the slope of the calculated energy dependence is rather independent of the details of the pion-photoproduction amplitude used in the calculation, provided it is consistent with the $N(\gamma,\pi)$ data, (2) the NN final-state interaction is essential in determining the energy dependence of the cross section; the commonly-used simple Feynman diagram estimate is incorrect, and (3) the calculated energy dependence is sensitive to the deuteron wave function as the photon energy exceeds about 700 MeV. The results have been used by the Argonne intermediate energy physics group in proposing new experiments at SLAC and CEBAF.

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f. The Δ Component in Nuclei and the $^3He(e,e'\pi)$ Reaction (T.-S. H. Lee and S. Nozawa*)

The Δ and pion components in nuclei can in principle be calculated from the model Hamiltonian described in Sect. I.A.a. The most interesting question to ask is: what are their experimental signatures? Following the suggestion by Lipkin and Lee, we have been exploring this question by considering the $^3He(e,e'\pi)$ reaction. We have predicted the dependence of the π^+/π^- ratio on the Δ component in the quasifree kinematic region. The calculation was done by folding the elementary $N(e,e'\pi)$ and $\Delta(e,e'\pi)$ amplitudes calculated from the model Hamiltonian described in Sect. I.A.b. into momentum distributions of the nucleon and the Δ in ^3He. We are now developing a computer program for calculating the most interesting triple coincidence $^3He(e,e'\pi^+p)$ cross section, which, in the quasifree kinematic region, can only originate from the $(\Delta^{++}NN)$ component in ^3He.

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g. Electromagnetic Nucleon Form Factor in a Relativistic Constituent Quark Model (F. Coester and P. L. Chung)

We have explored the electromagnetic properties of relativistic constituent quark models of protons and neutrons. The wave functions are spin-1/2 eigenfunctions of the four-momentum of the system. The simplest models depend on only two parameters, the constituent quark mass and a confinement scale. Such models can reproduce existing data within 15% for momentum transfers up to 4 GeV^2. Small anomalous magnetic moments of the constituent quarks can produce a much improved fit to the data. 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. A paper for publication is in preparation.

h. The Spin Structure of the Nucleon (F. Coester and W. H. Klink*)

Nonrelativistic composition of the quark spins yields results for the spin function of the proton 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 have studied this mechanism with a crude quark model assuming an unpolarized sea. It is possible to fit roughly both the empirical valence distributions and the spin-structure function in this fashion, but it is not possible to satisfy the Bjorken sum rule at the same time. Results are extremely sensitive to details of the transverse momentum distributions. It is necessary to investigate in detail the structure of more sophisticated Fock-space wave functions, which satisfy all symmetry requirements.

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i. Deep Inelastic Lepton Scattering by ^{3}He and ^{3}H (F. Coester, U. Oelfke,* and 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. A paper for publication is in preparation.

*University of Hannover, Hannover, West Germany

j. Relativistic Corrections to 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 on this work has been published.

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k. High Energy (p,2p) Reaction and Color Transparency (T.-S. H. Lee and G. A. Miller*)

It has been speculated that in the large momentum-transfer region, nuclear medium effects on hadron-hadron interactions in nuclei are negligible. This phenomenon, called the color transparency, is predicted by the QCD-motivated consideration that a large momentum-transfer reaction is dominated by a hadron wave function which has a small size in coordinate-space, and hence its induced color dipole interaction with the nuclear medium is very weak. We have been exploring whether this prediction has been verified in recent data for the (p,2p) reaction at 2-6 GeV. Our approach is to first carry out a standard calculation of all of the medium effects which can be rigorously predicted from the existing nuclear models and the NN cross section data. The deviation of our prediction from the data is then used to explore the underlying QCD mechanisms of color transparency. The calculation has been done within the Glauber theory. We have found that nucleon-nucleon correlations play an important role in determining the energy-dependence of large angle (p,2p) reactions. By using the Cohen-Kurath matrix elements and density-dependent Hartree-Fock wave functions to describe correlations in p-shell nuclei, we get a transparency for the $^{12}C(p,2p)$ reaction that oscillates less than the data. We are now exploring the model-dependence of our prediction by considering the consequences of the correlation functions generated from a $4\hbar\omega$ shell-model calculation of Haxton and a many-body calculation by Negele.

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ℓ. Pion Excess in ^{16}O (S. C. Pieper and R. B. Wiringa)

A significant part of the binding of nucleons in a nucleus comes from the exchange of virtual pions. This means that the expectation value in a nucleus of the number of pions per nucleon with momentum k, $n^{\pi}(k)$, will be different from the corresponding value for a free nucleon. This difference, $\langle\delta n^{\pi}(k)\rangle_A$, was computed seven years ago by Friman, Pandharipande, and Wiringa by expressing $\langle\delta n^{\pi}(k)\rangle$ in terms of expectation values of the pion components of the Argonne v_{14} or v_{28} potentials. They made calculations for the A = 2, 3, and 4 nuclei and nuclear matter. The nuclear matter results were used in local density approximation (LDA) calculations to compute $\langle\delta n^{\pi}(k)\rangle_A$ for heavier nuclei, such as ^{56}Fe.

The availability of our ^{16}O wave function (Sect. B.d.) allows us to now compute directly $\langle\delta n^{\pi}(k)\rangle$ for ^{16}O without using the LDA. We find a significantly smaller excess, $\delta n^{\pi}/A = 0.068$ compared to 0.098 in LDA. The $\langle\delta n^{\pi}(k)\rangle/A$ distributions for ^{16}O and ^{4}He are very similar.

m. Electromagnetic Pion Form Factor in a Non-local Nambu-Jona-Lasinio Model (C. Roberts)

A model developed as an approximation to QCD is used to calculate the electromagnetic pion form factor which describes the non-pointlike diffractive properties of the pion in elastic electromagnetic interactions. The calculation employs and further develops a non-perturbative approach to field theories which is crucial to our study of the low-energy sector of strongly interacting, non-Abelian gauge theories. Beginning with a non-local Nambu-Jona-Lasinio model, a bilocal bosonization technique is employed to obtain an effective action that is expressed completely in terms of bosonic field variables that can be identified with the mesons of the strong interaction spectrum. This approach has been very successful in describing those aspects of the meson spectrum that owe their origin solely to the strong interaction and the extension to electromagnetic interactions is of great interest in nuclear physics because it relates experimentally measurable quantities directly to underlying QCD degrees of freedom.

In calculating the pion form factor it is necessary to determine the strong $\pi\pi\rho$ vertex function which has been modeled using a simple dipole form in the past. The non-local Nambu-Jona-Lasinio model predicts a form for this function which differs remarkably from that used to date in phenomenological nuclear physics calculations. A much softer vertex is predicted. With the experience gained in calculating the $\pi\pi\rho$ vertex it is a relatively simple matter to complete the calculation of the electromagnetic pion form factor. Once this is completed, and the implications of the result for the model and QCD phenomenology are understood, many other quantities of interest may be calculated without too much difficulty: for example, the ω-ρ mixing part of the nucleon-nucleon potential. It is clear that such results, obtained from this model, can provide valuable input to nuclear physics calculations, providing QCD-based predictions for fundamental quantities and thereby replacing some of the guesswork in the phenomenological calculations of nuclear physics.

n. Partial-Wave Analysis of NN Reactions (T.-S. H. Lee and C. Fasano*)

We established the relationship between the partial-wave analysis of the $pp \rightarrow pn\pi^+$ reaction by Shypit et al. and the unitary formulation of the πNN problem. It is shown that the $N\Delta$ phases extracted by Shypit et al. are not exclusively due to the $N\Delta$ interaction. This work has been published.

We also have shown that the higher partial-wave NN amplitudes currently used in various phase-shift analyses are not compatible to the one-pion-exchange dynamics including the $NN \rightarrow N\Delta$ coupling.

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o. 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.

p. Multi-Λ Hypernuclei (A. R. Bodmer and Q. N. Usmani*)

We are continuing to study multi-Λ hypernuclei, in particular ΛΛ hypernuclei which contain two Λs. Further calculations and analysis of $^{10}Be_{\Lambda\Lambda}$ ($^{8}Be+2\Lambda$) are being made with the aim of obtaining information about the ΛΛ interaction from the binding energy of this nucleus. We also intend to make Monte Carlo variational calculations of light hypernuclei ($A\lesssim 6$) with two or more Λs, in the framework of the phenomenological model of hypernuclei 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.

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q. 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 that only with scalar self-interactions, in particular cubic-plus-quartic self-interactions, 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 general conditions on the scalar potential function required by the properties of nuclear matter at saturation, including the incompressibility coefficient K. These conditions depend on K and the effective mass M^* which 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 zero-temperature equation of state (EOS) 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 fairly 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. This work has been acccepted for publication.

r. Relativistic Mean Field Theory of Nuclei With a Vector Meson Self-interaction (A. R. Bodmer)

In our work (with C. E. Price) on general scalar potential functions in RMFT, which is described in Sect. A.q., we found that the (zero temperature) EOS consistent with the phenomenology of light nuclei is quite stiff, with rather little freedom left to vary the EOS, and in particular to obtain a significantly softer EOS. In the present study, we have investigated a one-parameter extension of the standard RMFT involving a self-interaction of the vector meson field (denoted by VSI). Such a VSI may be considered as phenomenologically simulating the effect of short-range correlations. The effective mass now depends on the strength of the VSI as well as on the vector coupling constant. We find that for a given M^*, K, the EOS can be greatly softened by increasing the strength of the VSI. For moderate strengths one can obtain quite similar EOS to those obtained from many-body theory if the corresponding effective masses are also comparable. Estimates of the spin-orbit splitting for light nuclei indicate that the associated constraints on the VSI are consistent with the values obtained from the saturation condition, and hence impose no further restriction on the EOS. Also, independent of the strength of the VSI, the energy dependence of the optical potential is consistent with M^* as obtained from the spin-orbit splitting of ^{16}O. One thus has available a one-parameter family of relativistic EOS for a given M^*. These families can then be used in the analysis of relativistic heavy-ion collisions or of neutron stars. This work is being prepared for publication.

B. NUCLEAR FORCES AND NUCLEAR SYSTEMS

(S. C. Pieper, R. B. Wiringa, V. R. Pandharipande,* and others)

Detailed quantitative studies of the consequences of realistic model Hamiltonians for nuclear systems are an important aspect of our work. Our goal is to achieve a description of nuclei from the deuteron to nuclear matter and neutron stars using a single parameterization of the interactions between nucleons. This model necessarily contains both two- and three-nucleon potentials and the potentials, of course, contain strong non-central correlations. There are two distinct aspects to this work: (1) developing realistic two- and three-nucleon interactions -- the widely used Argonne v_{14} is an example, and (2) developing many-body techniques for computing nuclear properties with such interactions -- our recent computation of the ground state of ^{16}O is an example.

In previous years we have concentrated on variational calculations of the few-body nuclei (A = 3, 4) and nuclear matter. We have continued to improve these calculations but we are now devoting most of our effort to nuclei from ^6Li to ^{16}O, and to few-nucleon reactions like $^3He(n,\gamma)^4He$.

The techniques used for A = 3 and 4 can be directly applied to A = 6-8, but for heavier nuclei such as ^{16}O we have had to develop a new cluster expansion. This method is quite successful. We expect that the calculations of heavier nuclei will place significant useful constraints on the choice of 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 electromagnetic probes. The variational Monte Carlo methods that we use make it relatively straightforward to compute the various expectation values required for comparison with electron scattering measurements of form factors, structure functions, knock-out reactions, etc. These calculations are an important aspect of our work.

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a. Improved Nucleon-Nucleon Potentials (R. B. Wiringa and R. Q. Hood*)

Realistic nucleon-nucleon (NN) potentials are the starting point of many microscopic nuclear structure studies. One of the standard models that has been used in few-body nuclei, light nuclei, nuclear matter, and neutron stars is the Argonne v_{14} potential. This model was developed in collaboration with R. A. Smith and T. L. Ainsworth in the early 1980's. It gave a good fit to then-existing np scattering data with a very simple form. New high-quality scattering data and phase-shift analyses have become available in the intervening years. At the same time, many-body calculational techniques have made significant progress which may make it possible to apply additional constraints to the NN potential. Improvements to the NN potential should be part of a general program in which consistent three-nucleon potentials and two-body exchange currents are also formulated and tests are made in the full range of many-body systems.

We have laid the ground work for constructing improved NN potential models. A data base with the latest phase-shift analyses has been prepared. A standard fitting routine has been adapted to our codes to improve the search procedure for potential parameters. The ability to fit pp as well as np scattering data has also been added. Our intention is to produce both an average charge-independent potential, and a charge-dependent potential. The latter could be used in studies of charge dependence in few-nucleon systems, and will affect the constraints placed on three-nucleon potentials.

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

Variational Monte Carlo studies of ^3H, ^3He, and ^4He are continuing, and we have begun calculations for the ground states of ^6Li and ^6He, and for some low-energy reactions of astrophysical interest. Improved variational wave functions have been developed which include spin-orbit correlations and three-body correlations for the three-nucleon potential, in addition to the usual six operator terms (central, spin, and tensor, and each of these times isospin).

The new trial functions give upper bounds within 3% of the 34-channel Faddeev wave functions for ^3H and the Green's Function Monte Carlo calculations for ^4He. The studies of ^6Li and ^6He are the first to treat them as six-body problems. The trial wave function has the one-body structure of a four-nucleon s-shell (alpha) cluster coupled to J=0, T=0, and two p-shell nucleons that are L•S coupled to either J=0, T=1 for ^6He or J=1, T=0 for ^6Li. Each of the two p-shell nucleons has a central p-wave correlation to the center of mass. The two-body correlations include three different kinds of central correlation (for the cluster pair, for pairs in the alpha, and for mixed pairs) and one set of non-central correlations acting between all pairs. Three-body correlations for the three-nucleon potential have also been added. At present, the computed binding energy of ^6Li is about the same as that of a separated deuteron and alpha computed with comparable wave functions. Further refinements in the trial wave function will be required to get the additional 1.5 MeV of binding that is experimentally observed.

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In collaboration with D. Riska, we have also made an ab initio calculation of the reaction $^3He(n,\gamma)^4He$. The thermal neutron capture cross section of 54 μb was recently remeasured by the Argonne weak interactions group. In previous theoretical work the ground states of ^3He and ^4He have been represented by shell-model wave functions. We have much better few-nucleon ground states and a ^3He-n scattering state with the correct scattering length. The impulse approximation gives a cross section of 6 μb, while addition of the minimal exchange currents that are consistent with the NN potential increases this to 69 μb. Thus this reaction is a very sensitive test of exchange current models. Next we will study the reaction $^3He(p,e^+\nu)^4He$, which is the source of the highest-energy neutrinos produced in the sun, and thus, although weak, contributes to all solar neutrino detection experiments.

c. 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 ^2H, ^3H, ^3He, and ^4He, 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 and three-nucleon potentials.

We are computing the ground state of the closed-shell nucleus ^{16}O with the same interactions that are being used in the light nuclei and nucleon matter studies (A.b. and 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. Two types of three-nucleon correlations are also included. 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. The program runs at more than 100 MFLOPS on a single processor of a Cray

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2S. The program was debugged by using various internal consistency checks and by reproducing our calculations of the alpha particle.

During FY 1989 we continued extensive variational searches for ^{16}O. We found that the three-nucleon correlation based on the three-nucleon potential provides a substantial (~7%) improvement in the energy. However a three-nucleon correlation based on two-nucleon considerations, while important for the alpha particle, gives little improvement to the binding energy of ^{16}O. Although further improvements to the ^{16}O variational wave function may still be possible, it now seems well established that the Hamiltonian being used (Argonne v_{14} plus Urbana VII) gives no more binding per nucleon for ^{16}O than for ^{4}He. We have also used our wave function to compute the density distribution, longitudinal structure function (see Fig. IV-5) and pion excess of ^{16}O. A paper describing preliminary results has been published.

We also made a first attempt at computing the ground state of ^{40}Ca using the cluster expansion. In this case it is not practical to compute all three- and four-nucleon clusters (as we do for ^{16}O) for a given configuration and we computed just a subset of all of the clusters. Unfortunately, the resulting statistical errors were far too large to be useful. We will have to devise a different method for choosing the clusters to be computed; the constraint of having a vectorizable algorithm makes this nontrivial. If we can produce a useful ^{40}Ca calculation we should also be able to calculate nuclear matter by using periodic boundary conditions.

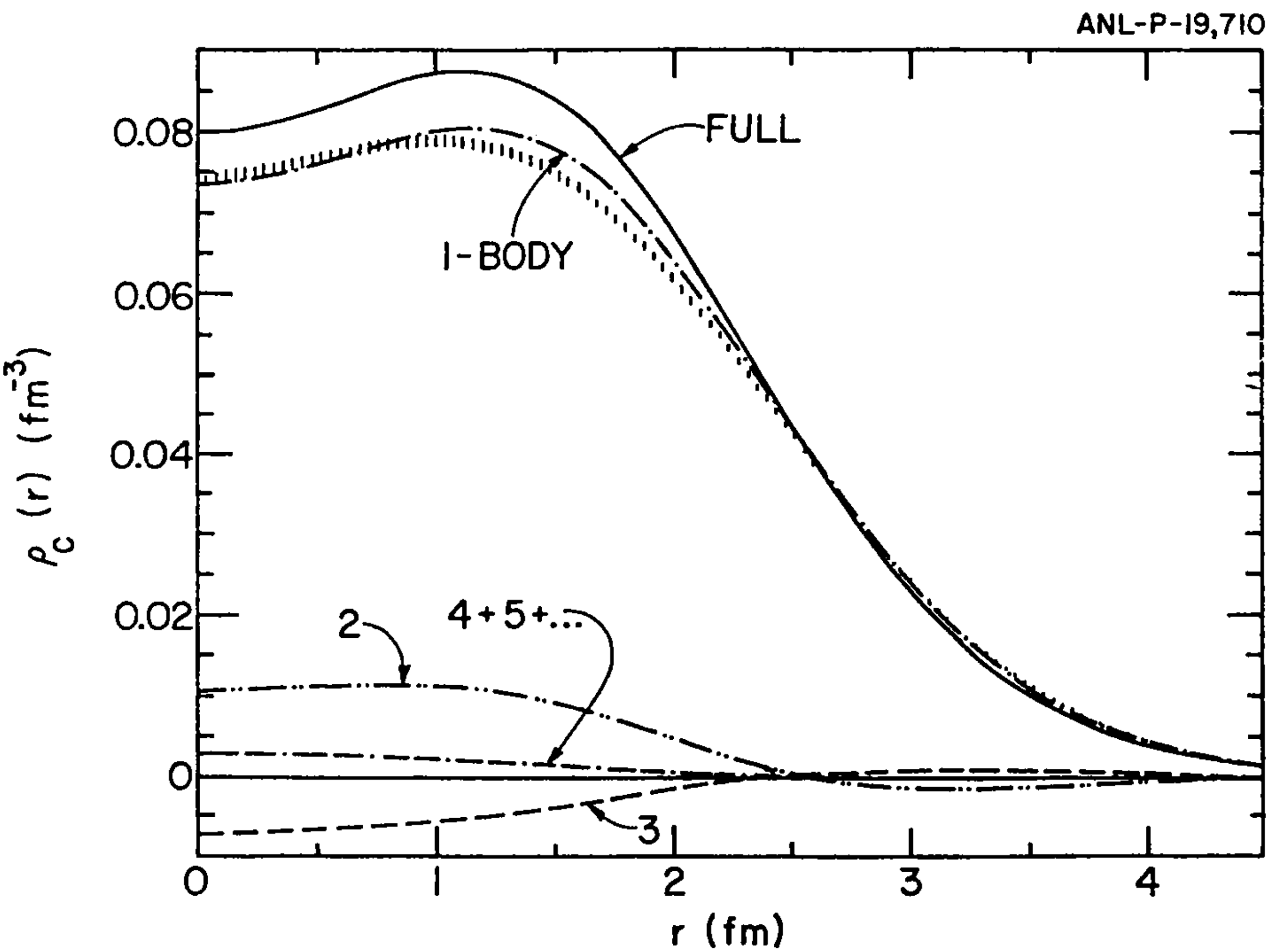

Fig. IV-5. Longitudinal structure functions for ^{4}He, ^{16}O, and nuclear matter. The solid curve gives the ^{16}O result using our variational wave function while the dashed curve is the result of a mean field calculation; the difference shows the effects of nucleon-nucleon correlations.

d. Nuclear and Neutron Matter Studies (R. B. Wiringa)

Nuclear and neutron matter remain an area of continuing interest. A major study of the dense nucleon matter equation of state (EOS), including calculations of neutron star properties and applications to medium-energy heavy-ion scattering, was completed in 1988 in collaboration with A. Fabrocini and V. Fiks (WFF). This work, coupled with our studies of light nuclei and ^{16}O, showed that the addition of plausible three-nucleon potentials to the nuclear Hamiltonian give a significant improvement in the calculated binding energies and density distributions. However, the relatively simple three-nucleon potentials studied so far cannot give detailed agreement for both finite systems and nuclear matter with one set of parameters. We are now generalizing our matter codes to study a wider range of possible models.

Renewed interest in dense neutron matter was sparked by the claimed observation early in 1989 of a rapidly spinning pulsar in the remnant of supernova SN1987A. According to work by the Stony Brook group, the Argonne v_{14} + Urbana VII Hamiltonian studied by WFF (and also used in our light nuclei and ^{16}O studies) is one of the few EOS that can support a rotation rate of 1.2×10^4 rad/s, while still supporting the slowly rotating mass of $1.44 M_0$ observed in radio pulsar PSR 1913+16. However, the EOS gives a superluminal sound speed at the high central densities required; this unsatisfactory situation probably occurs because of the stiffness induced by the strong short-range repulsive three-body potential. At high densities, four-body and higher-order potentials may be expected to play a role. The short-range terms should alternate in sign and will provide some softening of the EOS. We are now investigating possible approximations that may take higher-order many-body forces into account, without having to explicitly introduce additional potentials.

C. HEAVY-ION INTERACTIONS

(H. Esbensen, S. Fricke, S. Landowne, F. Videbaek, and others)

Our heavy-ion studies have concentrated on the application of coupled-channels techniques to reactions near the Coulomb barrier. In this way we seek to provide a consistent, unified, quantum-mechanical explanation of various phenomena which are currently being measured experimentally, such as sub-barrier fusion reactions, polarization effects in elastic and inelastic scattering, compound-nucleus spin distributions and transfer reactions. The channels considered consist of inelastic states in both projectile and target and of channels in which a few nucleons are exchanged between the projectile and the target. The fusion process is simulated by ingoing wave boundary conditions. We do not use imaginary potentials since we try to account explicitly for the total reaction cross section. 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.

In the past year we have focussed on one-nucleon transfer reactions. We use local transfer form factors and we have been able to include the longitudinal recoil correction, which is the most dominant recoil correction for reactions near the Coulomb barrier. We have reduced the number of coupled equations considerably by employing the rotating frame approximation in which one ignores the effect of angular momentum coupling. This approximation is often quite reasonable but it can be poor in special cases. We have therefore also developed programs that can handle the full angular momentum coupling in such cases.

a. Coupled-Channels Calculations of Heavy-Ion Reactions
(H. Esbensen, S. Fricke, and S. Landowne)

In our coupled-channels calculations of heavy-ion reactions we include the most dominant reaction channels that couple directly to the entrance channel and we simulate fusion by ingoing wave boundary conditions. We expect that this approach will enable us to reproduce measured fusion and elastic scattering data. This approach has previously been applied to reactions between different nickel isotopes where it gave a reasonable agreement with the measured fusion and quasielastic scattering data. Including a coupling to successive neutron transfers also yielded a good description of the measured angular distribution for one-neutron transfer.

A recent analysis of the elastic and inelastic scattering of ^{16}O on ^{58}Ni (see Sect. C.b.) indicated that better fits to the data were obtained when the nuclear coupling strength to the 2^+ state in ^{58}Ni was increased by 18% over the Coulomb coupling strength. We have repeated accordingly the reaction calculations for Ni+Ni using such an increased coupling strength, both in ^{58}Ni and ^{64}Ni. This led to a significant improvement in the comparison to the measured fusion data. The calculated angular distributions for elastic scattering are also in remarkably good agreement with the measurements for $^{58}Ni+^{64}Ni$ recently performed in Legnaro, Italy. This work has been submitted for publication.

We have also performed an analysis of reactions between different calcium isotopes, including low-lying excitations and one-nucleon transfers. For $^{40}Ca+^{40}Ca$ we obtained good agreement with the measured fusion and elastic scattering data. We have used this system to calibrate the ion-ion potential for different isotopes by scaling the nuclear radii according to measured RMS radii. This scaling procedure worked very well for the scattering of ^{16}O+Ca, Ni+Ni and Si+Ni isotopes. However, it does not work so well for the calcium isotopes. The predicted low-energy fusion cross sections for $^{40}Ca+^{44,48}Ca$ are much smaller than the data. It is very unlikely that this discrepancy can be explained by missing coupling strengths. In order to resolve this problem it is necessary to have additional measurements, both of the elastic scattering and of the transfer cross sections. This work has been published.

We have recently tried to analyze the scattering of $^{32}S+^{58,64}Ni$, where more complete data exist. Here it is also difficult to obtain a consistent description of the fusion and the elastic scattering data for the two nickel isotopes, although the inconsistency is not as serious as for the reactions between the different calcium isotopes mentioned above. New measurements are presently underway, and preliminary results are inconsistent with some of the old data. We have therefore postponed the completion of this study until the new data become available.

b. Coupled-Channels Calculations for Elastic and Inelastic Scattering (H. Esbensen and F. Videbaek)

We have applied our coupled-channels method to analyze the elastic and inelastic scattering of ^{16}O on various targets. Previous analyses were based on DWBA calculations using adjustable, energy dependent, complex nuclear potentials. Our approach is to use real, energy-independent nuclear potentials, and to include the most dominant reaction channels. The energy dependence of the effective potential for elastic scattering is therefore generated by explicit couplings. Our purpose is to see how well this approach works and to see if the deformation lengths, extracted by fitting the inelastic data, are consistent with those determined from DWBA analyses.

We find that the fits to the data for $^{16}O+^{58}Ni$ and $^{16}O+^{88}Sr$ are qualitatively as good as obtained previously. Moreover, the extracted deformation lengths for the 2^+ and 3^- target states agree with the old DWBA results within 10%. We have also obtained reasonable results for $^{16}O+^{40,48}Ca$ scattering although transfer channels, which we have ignored, may play a significant role for these systems. This work has been published.

c. Dispersion Relation for Effective Interactions (H. Esbensen, S. Landowne, M. S. Hussein,* and others)

One of the interesting phenomena observed recently in the analysis of heavy-ion collisions is an apparent dispersion relation satisfied by the optical potential for elastic scattering. 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.

We have demonstrated by examples that the equivalent local potential, generated by couplings to inelastic and transfer channels, also obeys the dispersion relation quite accurately when absorption is present. We have verified that the equivalent local potential is insensitive to the potential used in the entrance channel when solving the coupled equations. The fact that the equivalent local potential generated in realistic model calculations closely follows the dispersion relation adds theoretical support to the energy-dependent local potentials that have been determined empirically. This work has been submitted for publication.

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

The elastic scattering angular distributions have been measured at JAERI for the combinations $^{28}Si+^{58,64}Ni$ and for several bombarding energies near the Coulomb barrier. The data are reproduced well by coupled-channels calculations using an energy-independent potential. The significant difference observed between the two systems is attributed to the large effect of nucleon transfer couplings in the case of $^{28}Si+^{64}Ni$. This work has been published.

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e. Low-Energy Reactions with Heavy Deformed Nuclei (S. Landowne, C. H. Dasso,* and J. Fernández-Niello†)

Calculations for ^{154}Sm + ^{154}Sm collisions which account for the deformed surfaces have been carried out. The results indicate that the threshold for nuclear reactions is about 50 MeV below the nominal Coulomb barrier. Some specific features of such low-energy collisions are pointed out. This work has been submitted for publication.

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f. Single Neutron Transfer ^{238}U + ^{238}U Collisions (S. Landowne and G. Pollarolo*)

Single neutron transfer data for very low-energy ^{238}U + ^{238}U collisions were measured some time ago at GSI using radiochemical techniques. The original analysis seemed to indicate that the angular distributions were anomalous. We undertook a new analysis of these data. We initially attempted an analysis following the lines of the previous subsection, but because of the large range of the single-nucleon form factor, the deformation effects were not pronounced. However, we do obtain a good overall agreement with the data using a simple semi-classical formula. This work has been submitted for publication.

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g. Inverse Reactions and the Statistical Evaporation Model: Ingoing-Wave Boundary-Condition and Optical Models (S. Landowne, J. M. Alexander,* and M. T. Magda*)

Statistical model calculations which are used to calculate evaporation spectra of light particles emitted from hot compound nuclei often rely on transmission probabilities obtained from global, optical-model fits to elastic scattering data. There are, however, theoretical arguments against such a procedure. To focus attention on this problem, we have made calculations comparing transmission coefficients from optical-model calculations with corresponding ingoing-wave boundary-condition calculations. This work is in progress.

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D. NUCLEAR STRUCTURE STUDIES

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

The objective of this research program is to learn about the effects of strong residual interactions on nuclear structure. We utilize both deformed mean-field and many-body methods in our studies. The two approaches are complementary. In those instances when both are appropriate, such as the superdeformed states in the Hg region, one obtains particularly useful insights into nuclear structure problems. Our major interests include the study of the effects of angular momentum on nuclear structure and the correlations arising from the higher multipoles of the effective nuclear interaction. This research program includes a substantial collaboration with the experimental programs at Argonne.

In the past year, we have centered much of our effort on questions associated with superdeformation in the light Hg isotopes. We predicted that there was a large new region of superdeformed nuclides, centered in the light Hg isotopes, in which the superdeformed states become yrast at spins sufficiently low that they might be populated in heavy-ion reactions. Our calculations favored ^{191}Hg and ^{192}Hg as being the nuclides in which such states would be most accessible. We also found deep superdeformed potential wells for the higher-mass Hg isotopes. Our predictions were verified first by Janssens and collaborators in ^{191}Hg at ATLAS. Since then, superdeformed states have been identified in ^{190}Hg, ^{192}Hg, ^{193}Hg and ^{194}Hg at Argonne, Livermore, Berkeley and Daresbury. There is an intense effort going on at all of these laboratories to find other examples in this region. These discoveries show that the nuclear potentials that we use and the cranking method used for calculating high-spin states provide reasonable descriptions of the nuclides in this region. The problems that we are studying in these nuclides are: (1) the changes in the moment of inertia with angular momentum (2) the mechanism of nuclear decay from a superdeformed shape to the slightly deformed shapes characteristic of the ground states of the light Hg isotopes. We are studying this latter problem using our many-body wave functions that treat pairing and deformation modes on an equal footing.

An active area of research in the past few years is the occurrence of diabolic points and Berry phases in nuclear structure problems. Until now, most studies have concentrated on pair-transfer reactions. In the vicinity of a diabolic point in (λ,ω) parameter space one expects to see a sharp decrease in the pair-transfer cross section at some critical angular momentum. Such a signal has not been clearly seen and might be obscured by the fact that there are many partial waves contributing to the pair-transfer cross section at each energy and by uncertainty in the reaction mechanism. This has prompted us to look for clear-cut manifestations of diabolic points in nuclear structure phenomena. We find such manifestations in single-particle energy level crossings in a multi-dimensional deformation space. It should be experimentally easier to identify these diabolic points in superdeformed nuclides, than in more normally deformed ones.

We have investigated various reactions on A=13,14 nuclei within the 1p-shell model.

a. Superdeformation in ^{191}Hg (R. R. Chasman, E. F. Moore, R. V. F. Janssens, I. Ahmad, T. L. Khoo, F. L. H. Wolfs, D. Ye,* K. B. Beard,* U. Garg,* M. W. Drigert,†, Ph. Benet,‡, Z. W. Grabowski,‡ and J. A. Cizewski§)

Based on our calculations in the region A=190, it appeared that the most likely nuclide for finding superdeformed states was ^{191}Hg. The two criteria that we have used for determining likely nuclides are: (1) the superdeformed minimum is at least 2-MeV deep in a cranked Strutinsky calculation; (2) the superdeformed state is yrast or near yrast at angular momentum values that are accessible in heavy-ion reactions. Our calculations suggested that ^{191}Hg and ^{192}Hg were the best candidates for study. An experimental study of the former nuclide was initiated by the heavy-ion gamma-ray spectroscopy group at Argonne. A superdeformed band was found having transition lifetimes in good agreement with the value obtained from our calculated value of the quadrupole deformation (axis ratio of 1.65:1). The moment of inertia of the superdeformed band found in these experiments was in fairly good agreement with our calculated value of 110 $\hbar^2$ (MeV)$^{-1}$. This was the first observation of superdeformation in the mass region A=190. The results of this study have been published.

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b. Superdeformation in ^{192}Hg (R. R. Chasman, I. Ahmad, M. P. Carpenter, P. Fernandez, R. V. F. Janssens, T. L. Khoo, E. F. Moore, S. L. Ridley, F. L. H. Wolfs, K. B. Beard,* U. Garg,* D. Ye,* Ph. Benet,† and M. W. Drigert‡)

According to our calculations, the second most plausible nuclide for searching for superdeformation near A=190 is ^{192}Hg. An experimental search for superdeformation in this nuclide was carried out by the heavy-ion gamma-ray spectroscopy group at the ATLAS facility. A superdeformed band was found in ^{192}Hg. Again the measured transition probabilities in this band were in good agreement with the values predicted by our calculations. The average moment of inertia found in this nuclide agrees well with the calculated value. However, there is a large systematic variation in the moment of inertia that is not given by our calculations.

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c. Moments of Inertia in Superdeformed Bands (R. R. Chasman)

In our original calculations of the properties of superdeformed states in the region A=190, the emphasis was on high-spin states. Accordingly, we have not included pairing effects in our calculations as they are not very important at high spin. Secondly, of necessity, pairing effects should be quite small in superdeformed configurations because one gets the large shell effects needed for superdeformation when the level density near the Fermi level is small. As the superdeformed bands in the A=190 region continue to rather low spins ($I \sim 10$), the effects of pairing do show up in these superdeformed bands by giving rise to variations in the moment of inertia of the superdeformed band. The standard treatment for treating pairing in rotational bands is a cranked quasi-particle method, using a gap parameter. However, when pairing effects are small the quasi-particle description breaks down completely (pairing collapse). We are developing an alternate treatment of the effects of pairing on superdeformed states.

d. Transition from Superdeformed to Slightly Deformed Shapes (R. R. Chasman)

A rather interesting general question is: "how does a quantum mechanical system make transitions between states that have very different properties?" This question gains increasing urgency when the transition is fast and it occurs in a chain of few gamma transitions (one-body operators) connecting the superdeformed band and a near-spherical ground-state band in the Hg isotopes. We have begun an exploration of this problem, using a many-body wave function that we have been developing for the past few years. Using these wave functions, we can handle a very large valence space consisting of ~100 proton orbitals and ~100 neutron orbitals. Each of the many-body wave functions includes $\sim 10^{10}$ different configurations. We have used the quadrupole interaction strength as a generator coordinate to construct a superdeformed ground state, a state with the ground-state deformation, and several states with deformations intermediate between these two. We find that if only the superdeformed and ground-state wave functions are included in a diagonalization, the transition matrix element between the two states is negligible. However, when the intermediate states are included in diagonalizations, this transition is speeded up by 20 orders of magnitude. Also, we find that the decay proceeds to many of the states of intermediate deformation as well as the ground-state band. It is interesting to see that there is no simple correlation between the deformation of a state and the transition probability from the superdeformed state. This is because the transition matrix element depends primarily on small pieces in the wave function, and so on relative phases of the relevant configurations. A report of this work was presented at the Symposium on High Spin Properties in Nuclei at Copenhagen. Calculations are continuing on this problem.

e. Diabolic Points and Berry Phases in Deformation Space
(R. R. Chasman and P. Ring*)

In a one-dimensional parameter space, the no-crossing rule of quantum mechanics holds; i.e. states with the same quantum numbers cannot cross. However, when the parameter space is multi-dimensional such states can cross without interacting. This crossing without interaction occurs only under special circumstances; when the interaction vanishes between the states for the values of the parameters in at least two dimensions of the parameter space. This is a diabolic point, and it can be identified by making a path around it in the parameter space. If one fixes the phases of the wave functions at each point along the circuit, by demanding that the overlap between the lowest eigenstates is positive for points i and (i+1), one gets an overlap of -1 when the path is complete only if it encloses a diabolic point. Earlier studies of this phenomenon have dealt with the (λ,ω) space of particle number and angular momentum. So far, experimental searches based on these studies have not been successful. We have carried out calculations in a parameter space consisting of the different deformation multipoles. Using a realistic single-particle potential, we have utilized the Berry phase technique to verify the existence of many diabolic points in this deformation space. We have looked at the crossings of single-particle states having the same values of the quantum

*Technical University of Munich, West Germany, and Lawrence Berkeley Laboratory, Berkeley, CA numbers π and Ω and find that they interact more strongly in a one-dimensional quadrupole deformation space when the differences between the N_z quantum numbers of the two states become smaller. This means that diabolic points can be most easily identified in superdeformed nuclides. We note that these diabolic points constitute the first discussion in nuclear structure studies of this phenomenon for a time-reversal invariant Hamiltonian. We also note that the existence of these points has serious negative implications for the use of the Gaussian Overlap Approximation in generator-coordinate calculations.

f. Single Particle States in the Heaviest Elements
(I. Ahmad and R. R. Chasman)

The search for superheavy elements has been a large-scale effort for the past 25 years or longer. Theoretical guidance in this area has not proven very useful because the predictions of superheavy lifetimes are so sensitive to the exact spacings of single-particle energy levels. Rather than using single-particle energy levels taken from some parameterization of the potential, it seems worthwhile to see what can be inferred about these level spacings making use of nuclear structure information in the heavy deformed actinides. We have been looking at the single-particle energy levels in N=153 nuclides. The calculated signatures obtained for the orbitals of interest can be combined with experimental studies to determine the positions of several spherical states above the N=184 neutron gap. The determination of these level positions necessitates the removal of energy shifts due to pairing from the experimental data.

g. Superdeformation near A=80 (R. R. Chasman and E. F. Moore)

We are continuing the search for new regions of superdeformation, using a cranked Strutinsky method. We have carried out a series of calculations for nuclides in the mass region A=80 and find that there are a few nuclides in this region that might have superdeformed bands that can be populated in heavy-ion reactions. Further calculations and investigations of experimental reaction cross-sections will be carried out.

h. 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†)

The known superdeformed bands in the mass region A=150 are associated with large gaps in the neutron single-particle spectrum at N=86, and large gaps in the proton single-particle spectrum at Z=64 and Z=66. Our calculations of superdeformation in this region also show a large gap at N=80 and predict that ^{143}Eu is the most likely nuclide to have a superdeformed band arising from the N=80 gap. Based on these calculations, a search has been made for superdeformation in ^{143}Eu. The experiments that have been carried out to date have identified a superdeformed band in gamma-gamma coincidence matrix studies. The discrete coincidences have not yet been observed and it is not yet clear whether the superdeformed band is actually in ^{143}Eu or ^{144}Gd. The moment of inertia of the superdeformed band observed in the gamma-gamma matrix is in good agreement with the value of 67 h^2 MeV-1 that we have calculated for ^{143}Eu.

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i. Assessment of the 1p-Shell Model for A=13,14 Nuclei

(D. Kurath, K. Amos,* L. Berge,* and D. Koetsier*)

We have carried out an analysis 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 are consistent with this suppression and to consider the contributions of other multipoles with the same value of J.

At higher momentum transfer, q ~ 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.

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j. Deformation of Neutron-Rich Nuclei and the Neutron Halo
(D. Kurath)

Recent experiments[1] with radioactive secondary beams give evidence for a neutron halo when beams such as ^{11}Li and ^{11}Be impinge on heavy targets. A study of the wave functions gives an interpretation of the behavior of these particular nuclei.

It has long been known that wave-functions generated from a Nilsson model of the 1p-shell have a strong overlap with the low-lying wave functions of an interaction calculation for nuclei in the valley of stability. In these cases the deformation is prolate for the first half of the shell and oblate in the second half. When there is a large neutron excess this changeover occurs at an earlier mass number because for oblate deformation there are two close low-lying Nilsson levels compared to one for prolate deformation as one sees in Fig. IV-6. The comparison between interaction ground-state wave functions and generated wave functions confirms the oblate deformation for ^{8}He, ^{9}Li and ^{10}Be.

The large gap to the next Nilsson level suggests much weaker binding for subsequent neutrons. The observed 2n binding energy in ^{11}Li is only 158 keV and the 1n binding energy in ^{11}Be is 500 keV. This is much less than the binding for the seventh and eighth neutrons in other 1p nuclei such ad ^{12}Be, ^{13}B and ^{14}C where the binding is more than 3 MeV. Therefore the presence of two types of bound neutorns (leading to a halo) is much more pronounced for ^{11}Li and ^{11}Be. An idea of the degree of difference could be obtained by calculation with a finite deformed well using the known binding energies of the last neutrons.

[1]I. Tanihata, Nucl. Phys. A488, 113c (1988).

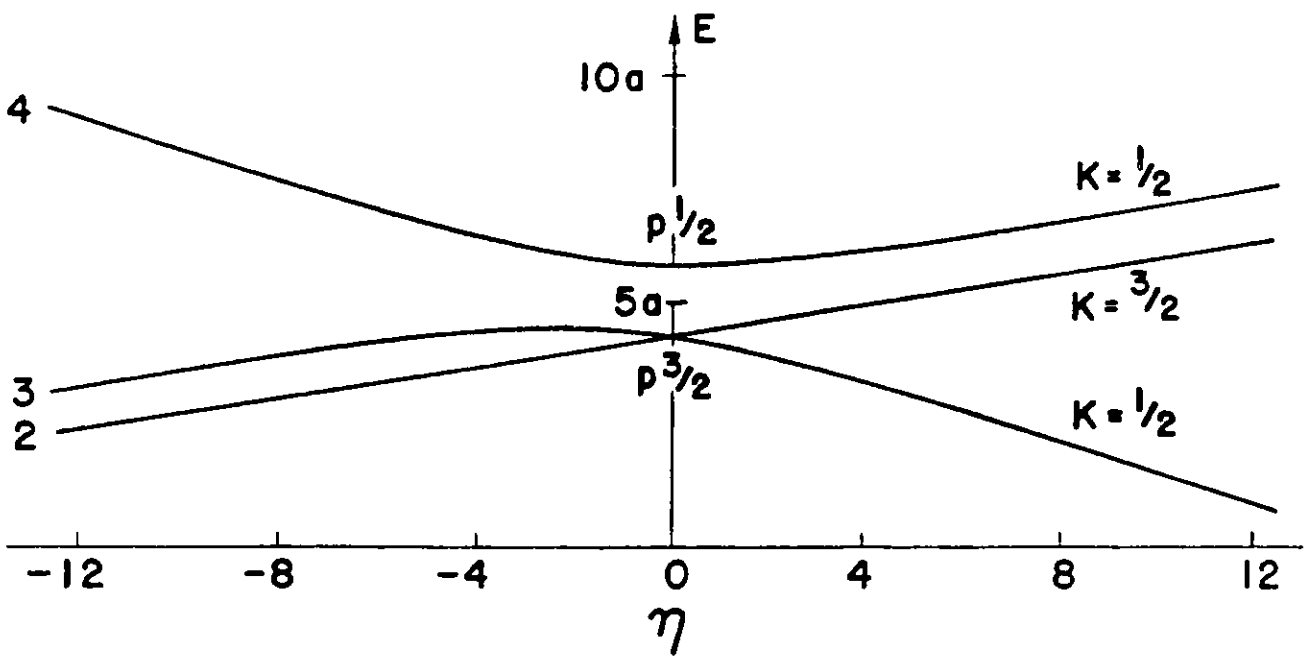

Fig. IV-6. Energy levels of the 1p shell as a function of the parameter η (according to Nilsson). The energy scale is plotted in units of the spin-orbit strength a.

E. FUNDAMENTAL PROBLEMS IN QUANTUM MECHANISMS

(H. Esbensen, M. Peshkin, and P. S. Sigmund*)

We have explored several theoretical issues concerning the Aharonov-Bohm Effect and Ehrenfest's theorem. A new concept for measuring the electric dipole moment of the neutron has been developed. We have studied the Barkas effect in a dense medium.

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a. Lessons Learned from the Aharonov-Bohm Effect
(M. Peshkin and A. Tonomura*)

We have completed a review of the experimental measurements of the Aharonov-Bohm effect and the theoretical issues that the experiments have now settled. The decisive quantitative experiments carried out at the Hitachi Advanced Research Laboratory agree with the predictions of quantum mechanics using single-valued wave functions, with precision on the order of .02 flux units. The theoretical analysis deals with the implications of the experiments for quantum mechanics in multiply-connected regions and for locality and causality in quantum mechanics. This work has been published as a monograph.[1]

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[1] "The Aharonov-Bohm Effect", by M. Peshkin and A. Tonomura. Lecture Notes in Physics, No. 340 (Springer-Verlag 1989).

b. The Electric Aharonov-Bohm Effect (M. Peshkin)

Surprisingly, the electrostatic version of the Aharonov-Bohm effect has not previously been analyzed except in a WKB approximation which is too crude to be a useful basis for discussions of fundamental questions in quantum mechanics. A more general analysis has now been carried out, subject only to the approximations of nonrelativistic quantum theory and the avoidance of induced magnetic fields when the electric fields are turned on and off. One new result is a demonstration of causality within the framework of the approximations used. This work has been published.[2]

[2] Loc. cit., pp. 27-28.

c. Locality in Quantum Mechanics in a Multiply-Connected Domain
(M. Peshkin)

One well-defined test of locality is the applicability of Ehrenfest's theorem, which requires that the rate of change of the expectation of the momentum equals the expectation of the external force. It has often been observed that Ehrenfest's theorem appears to be violated in the scattering of electrons from a magnetic flux in a multiply-connected region. I have now shown that the external force must be supplemented by a force of reflection from the boundaries in a multiply connected region, and when that is done Ehrenfest's theorem is restored. This work has been published.[3]

[3] Loc. cit., pp. 31-32.

d. A New Concept for Measurement of the Electric Dipole Moment of the Neutron (M. S. Freedman, M. Peshkin, G. R. Ringo, and T. W. Dombeck*)

The current experimental limit on the neutron electric dipole moment (NEDM) is about 1×10^{-25} e-cm, according to both the Ramsey group and the Lobashov group. The uncertainty is currently dominated by systematic errors, and both groups expect to be able to improve their sensitivity significantly over the next few years, perhaps by a factor around ten or twenty. Beyond that, a new approach may be needed because the accuracy obtainable by current methods is limited by the uncertainty principle, at least with foreseeable neutron sources and achievable electric field strengths.

The existing experiments fundamentally measure an energy or frequency shift in a nuclear magnetic resonance experiment. The electric energy difference W between spin-up and spin-down states is given by $2\mu_e E$, where μ_e is the NEDM and E is the applied electric field. For a single neutron, the uncertainty principle results in $\Delta W \sim \hbar/\tau$, where τ is the neutron lifetime. For N neutrons, that limit is reduced by $\sqrt{N}$. Using realistic projected values of E and N, the experimenters expect that a sensitivity of a few times 10^{-27} e-cm is the best they can hope to achieve. Any approach that basically measures an energy or frequency shift in a uniform electric field shares this fundamental limitation. The same is true of an ordinary Mach-Zehnder interferometry experiment with a uniform electric field E in one arm of the interferometer so that the momentum p in that arm is shifted by $\Delta p = (p/m)\mu_e E$.

In anticipation that greater sensitivities may be needed, we have been exploring speculative new concepts for measuring the NEDM by interference or polarimetry experiments using ultra-cold neutrons (UCN). In this approach, confined neutrons are polarized perpendicular to a horizontal direction x in an "accelerator" containing a strong electric field gradient $\partial E_x/\partial x$ and a uniform magnetic guide field B_x, so that the spins precess around the x axis. Initially, the neutron wave function has the form $\psi(0) = \{|+\rangle + |-\rangle\}\phi(x)$, where $\phi(x)$ is a wave packet and the spin wave function is shown in terms of the eigenstates of σ_x. Over time, the two spin states acquire a phase difference due to the electric and magnetic fields, but more importantly, their wave

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packets become spatially separated due to the electric field gradient. We call such a state "bipolarized", in contrast to an ordinary transversely polarized state for which the spin wave function simply multiplies a single spatial wave packet. In the bipolarized state, the two packets with opposite spin acquire a velocity separation proportional to the time and a spatial separation proportional to the square of the time. The wave function is then given by $\phi(t)=\{|+>\}\ \phi_{+}(t) + \{|->\}\ \phi_{-}(t)$. Several possible accelerator designs have been considered. Of these, the most promising appear to be an open-ended box in which neutrons can be confined by reflection from a curved roof and thereby kept in the accelerating electric field gradient for some 5-10 minutes. Preliminary calculations indicate that such a device can retain a useful number of neutrons.

After 500 seconds, the neutrons are caused to fall about 60 cm under the influence of gravity and then to strike a 45° mirror so that they again move in the x direction, but now with one component of the bipolarized beam slightly above the other. The remainder of the experiment is similar in principle to the Colella-Overhauser-Werner gravity interferometer. The two beams acquire a phase difference proportional to their gravitational energy separation, which is proportional to μ_e but much greater than $2\mu_e E$, and be detected within the limitation imposed by the uncertainty principle. The phase shift can be detected as a shift in transverse polarization when the two spin states are allowed to interfere after another 500 seconds. Our interferometer differs from a conventional one in that the two interfering wave packets are never separated by as much as one nanometer, so that some daunting technical problems are avoided.

A preliminary report on this work was presented at the Third International Symposium on Fundamental Questions in Quantum Mechanics, Tokyo, 1989.

e. Barkas Effect in a Dense Medium: Stopping Power and Wake Field
(H. Esbensen and P. Sigmund*)

We have studied the polarization field induced by a heavy charged particle penetrating through a random medium. We have derived a general expression which includes contributions to first and second order in the charge of the particle, and it determines the stopping power up to third order. For a dilute gas, the stopping-power formula reduces to the one that can be derived directly from perturbation theory, applied to an isolated atom and molecule. The interaction between a charged particle and the medium is characterized by two functions, the well-known dielectric functions $\epsilon(k,w)$ and a function $Y(k,s,k',w')$ which depends on two sets of wave numbers and frequency variables. We have derived explicit expressions for Y in four different cases: (1) for a random medium of harmonic oscillators from the classical equation of motion, (2) for a classical electron gas from Boltzman's transport equation, (3) for a system of Hartree atoms from quantal perturbation theory, and (4) for the Fermi gas. The different cases yield identical results in those limits where such is to be expected.

We have, in particular, evaluated the Barkas effect on the stopping power (to third order in the charge) for a medium of classical harmonic oscillators. The isolated classical oscillator and the classical electron gas emerge from this as simple limiting cases. The classical description applied to distant collisions only.

Quantitative results have been obtained numerically for a quantal electron gas with the Fermi motion disregarded (static electron gas). The results compare well with recent experimental data for protons and antiprotons stopping in silicon. We find that the Barkas correction to the stopping power is mainly positive for positively-charged particles, but it turns negative at low speed, in agreement with existing results for the harmonic oscillator.

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The second-order contribution to the induced field (or wake field) contains a higher harmonic, i.e. a field that oscillates at twice the standard wave number. This alters the wake potential dramatically behind the penetrating particle at low velocities. This effect is possibly an explanation for observed anomalies in molecular-ion energy-loss spectra.

The relative significance of the Barkas correction to the stopping power and the wake field increases with increasing electron density in the medium. This work has been accepted for publication.

ATOMIC AND MOLECULAR PHYSICS RESEARCH

Atomic Physics research in the Physics Division consists of three principal ongoing programs:

(1) Fast ion-beam/laser studies of atomic and molecular structure (L. Young),

(2) Interactions of fast atomic and molecular ions with solid and gaseous targets (E. P. Kanter and Z. Vager),

(3) Atomic physics at ATLAS and the ECR source (R. W. Dunford and H. G. Berry)

A fourth program, high-resolution laser-rf spectroscopy with beams of atoms and molecules, ended in FY 1990 following the retirement of Dr. W. J. Childs. In addition, a continuing program in theoretical atomic physics is staffed primarily by visiting scientists. A small effort (supported by Laboratory Discretionary funding) continues 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.

A highlight of research in 1989 at the Dynamitron has been the utilization of the new time-and-position-sensitive particle detector "SAM" (Segmented Anode Muppats), and the older MUPPATS detector in the same experiment. We are thus able to detect and distinguish both light and heavy fragments from the same molecule with greatly improved time and spatial resolution. Several new molecular-ion structures have been measured using this technique. At ATLAS, photon coincidence experiments gave precise lifetime measurements in hydrogen-like and helium-like nickel, as tests of quantum-electrodynamics; also at ATLAS, the new ECR ion 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: we measured the photon spectrum of francium-like uranium; we made Auger-electron measurements in highly-ionized neon and silicon; and we made the first accurate measurements of any ECR source velocity profile, using a collinear-laser excitation in argon. At BLASE, we used a new high-resolution technique in fast-beam/laser spectroscopy, a Raman double-resonance technique, using it to measure hyperfine structures in ionized scandium, and we have new high-precision measurements on the hyperfine and spin-rotation structures in ionized molecular nitrogen. In addition, in our neutral beam measurements, a systematic study using the rf double-resonance technique has been completed on the group IIA monoxides LaO, YO, and ScO.

The Argonne Tandem Linear Accelerator System (ATLAS) offers unique opportunities for atomic physics research using intense beams of highly-charged heavy ions at high and well-controlled velocities. The new upgrades now in progress, which replace the Tandem injector with an ECR source on a high-voltage platform, plus a new series of low-velocity superconducting rf resonators will be highly beneficial to the atomic physics program. We now have more intense beams of low- to medium-charged ions (up to mass 100, including the rare-gas ions). The new facility is also able to accelerate heavy ions up to the heaviest in the periodic table. This new "uranium accelerator" has already allowed us to look at the atomic structures of these multiply-charged heaviest ions for the first time, using the ECR source in a stand-alone mode. We anticipate a strong expansion of our atomic-structure program for these heavier ions at ATLAS as we probe the many-body relativistic correlations in the higher-charged systems not accessible to study in the lighter ions.

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 a precise measurement of metastable states in hydrogen-like and helium-like nickel. Previous measurements (in nickel at Argonne, and in lower-Z ions elsewhere) had been standard beam-foil decay-curve measurements which suffered from background and blending problems, and consequently were of precision too low to test quantum-electrodynamic corrections to these lifetimes. Lifetime measurements have also been made in metastable states of two-electron bromine and two-electron nickel to test calculations of forbidden decay modes.

Atomic Physics experiments of low-energy highly-stripped ion beams continued to use 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. We constructed two beam-lines and associated target/detection systems to take advantage of a "window of opportunity" for atomic physics experiments at this unique facility. This window will be essentially closed late in FY 1990, when the injector becomes part of the on-line ATLAS system.

The high-voltage platform of the ECR source injector allows us to make measurements in a range of ion-beam velocities that is not accessible at any other facility. This makes the installation unique for many experiments involving low-to-medium velocity multiply-charged ions. Experiments have included both collision experiments and atomic structure measurements.

We have studied the velocity dependence of the cross sections for state-selective electron capture of several two-electron projectiles. Several experiments on secondary-electron production in ion-atom collisions studied the spectroscopy of auto-ionizing states in highly-ionized neon and silicon. Initial measurements with a polarized sodium target, constructed and tested in 1989, were made using N^{5+} ions from the ECR source. We measured the Stokes parameters of the polarized ultraviolet light emitted after electron-pickup.

Close collaboration continues between Drs. Young, Azuma, Mansour and 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. Polarization measurements in heavy ions (N^{5+}) at the ECR source and protons at BLASE are underway.

Our theoretical program has been staffed by visitors during 1989. 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 Professor L. Curtis at the University of Toledo, and Professor J. Sapirstein at 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, are relevant to Sapirstein's work. Systematic variations in the structure of many-electron systems are the focus of Curtis' work. 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 enhanced several projects in the atomic program. In addition to several collaborations, he has begun work on a book on sputtering. He will return to complete his appointment in June 1990.

V. HIGH-RESOLUTION LASER-rf SPECTROSCOPY WITH BEAMS OF ATOMS AND MOLECULES

Our effort during the past year has again been divided between structual studies of diatomic radicals and selected many-electron atoms. The hyperfine structure of the isoelectronic molecules PrO and CeF was studied in detail. Although the electronic configurations are nominally the same, the observed hfs differs completely because the metal-centered odd electrons in PrO interact with the I=5/2 ^{141}Pr nucleus, while those in CeF interact with the I=1/2 of the ^{19}F (on the other end of the molecule). In-depth studies of the spin-rotation and hfs interactions were made in ^{87}Sr^{19}F for comparison with the isoelectronic molecule ^{89}Y^{16}O studied earlier. The SrF measurements were extremely difficult because of the 100-fold greater intensity of ^{86,88}Sr^{19}F lines. This is the heaviest diatomic molecule for which precise measurements of the hfs at both atomic sites have yet been made. In order to test the influence of the oxygen atom on the hfs of YO (where the Y-centered odd electron interacts with the I=1/2 of ^{89}Y), similar measurements were made in YS. In this case, where the S atom has been substituted for the O, the hfs at the Y site and the spin-rotation interaction for the molecule as a whole are both affected substantially.

To further test the hfs of atoms with levels built on 3 open electron shells, studies were made of hfs in excited levels of both Eu I and Nd I. In the first case, the configuration studied was $4f^7 5d6s$ while in the second $4f^4 5d6s$. A point of particular interest for the Eu is that the 4f shell is exactly half filled so that only the 5d and 6s electrons contribute to the hfs. For the Nd, the point of interest is the unusually large value of the orbital angular momentum (L=8) for the states studied. Ab initio calculations are in progress. An investigation was made of an extremely dense (20 lines within 2 Angstroms) spectral region of Tb I. Efforts to classify the lines by comparing observed lower-state hfs with previously known results for low-lying electronic levels were only partially successful. A Doppler-free laser-fluorescence study of a transition in ^{178}Hf at 7131.81 Å was made to assess the feasibility of a key step toward production of an energetic beam of ^{178}Hf in a nuclear isomeric state with $J,\Pi=16^+$.

During the past year emphasis was placed on completing a number of experiments in progress; the analysis and writeup of this work was intentionally deferred to CY 1990.

a. Hyperfine Structure of Low Electronic States of PrO by Molecular-Beam Laser-rf Double Resonance (W. J. Childs, Y. Azuma, and G. L. Goodman*)

Considerable time was spent studying the isoelectronic molecules PrO and CeF. In PrO, laser-rf double resonance was used to measure precisely the hyperfine structure of the electronic groundstate (Ω = 3.5) for all J-values up to 60.5. The measurements reveal that the splittings are negative at the lowest J-values, and then increase almost linearly with J, becoming positive for all J $\gtrsim$ 5.5. The measured J-dependence shows that previously published results inferred from optical spectra are wrong and once again demonstrates the need for direct measurement of hfs splittings. The unusual J-dependence appears to arise from off-diagonal interactions between the ground- (Ω = 3.5) and first-excited (Ω = 4.5) electronic states. The double-resonance method was accordingly used to measure the hfs in the excited state, and the hfs was found to decrease rapidly with increasing J. The molecular electronic states X (Ω = 3.5) and A (Ω = 4.5) are closely related to states of Pr^{2+} ($4f^26s$) coupled with the oxygen ion O^{2-} with a full 2p shell. If we denote the electronic angular momentum of the $4f^2$ core as $\vec{J}_c$ and the spin of the 6s electron as $\vec{s}$, then as a start we must consider the operators $H_{rot} = B(\vec{J} - \vec{J}_c - \vec{s})^2$ and $H_{hfs} = b\vec{I}\cdot\vec{S}$. The total hfs in the state X or A is then composed of two parts: (1) the intrinsic hfs caused by evaluating H_{hfs} within each state, and (2) that due to the mixed interaction $\langle X|H_{hfs}|A\rangle\langle A|H_{rot}|X\rangle$ or $\langle A|H_{hfs}|X\rangle\langle X|H_{rot}|A\rangle$, i.e. the off-diagonal hfs between the states of different Ω. In order to calculate these matrix elements we need a specific model forthe coupling of electronic angular momenta. We have adopted the coupling scheme $J_c,\Omega_c,\sigma,\Omega$, where Ω_c gives the projection of $\vec{J}_c$ on the internuclear axis and σ gives the projection of the outer electron spin on this axis. In this scheme the X state is 4, 4, -0.5, 3.5 and the A state is 4,4, 0.5, 4.5. The necessary Racah algebra has been carried out and it is found that the model is in very close agreement ($\simeq$1-2 %) with experiment if the interaction strengths are regarded as adjustable parameters. The best-fit values determined for the off-diagonal hfs parameters are very nearly equal and opposite (as expected from the opposite signs of the energy denominators), but the parameter values for the diagonal terms are found to be very different for the two states. This result is not satisfactory, and the hfs Hamiltonian is accordingly being expanded to include additional terms in a continuing effort to achieve a realistic understanding of the structure.

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b. <u>Doppler-Free Spectroscopy of a CeF Molecular Beam</u>
(Y. Azuma, K. L. Menningen, and W. J. Childs)

The molecule CeF is of special interest because it is isoelectronic with the extensively studied molecule PrO. Only a single band of the spectrum of CeF has been rotationally analyzed so far. It is believed to be the $v' = 0 \leftrightarrow v'' = 0$ band between a low-lying excited electronic state and a $^2\Phi_{5/2}$ ground state. The ground state has not yet been identified with certainty, however. In the present study, the wavelengths for the P, Q, and R branches were systematically measured using well-cataloged I_2 lines as a standard. The rotational constants of both the lower and upper states were precisely determined. Careful comparison of the hfs splittings observed in the three branches as a function of J established that the optical hfs arises almost entirely from hfs splittings in the excited electronic state; the ground-state splittings are too small to be measured at present. Direct comparison with the situation in the isoelectronic system PrO is unfortunately limited by the absence of a stable odd-A isotope of Ce. The hfs observed in CeF is due to the Ce-centered electrons sensing the fluorine nuclear spin, while in PrO the Pr-centered electrons are sensing the Pr nuclear spin.

c. <u>Precise Measurement of the hfs in the $X^2\Sigma^+$ State of $^{87}Sr^{19}F$</u>
(Y. Azuma, W. J. Childs, T. C. Steimle, and G. L. Goodman*)

Our previous laser-rf double-resonance study of the X state of SrF, published in 1981, determined the spin-rotation and (fluorine) hfs constants precisely for both $^{88}Sr^{19}F$ and $^{86}Sr^{19}F$. Careful searches at that time for spectral lines due to the $^{87}Sr^{19}F$ molecule were unsuccessful due to (1) the 10-times smaller abundance of the ^{87}Sr and to (2) the additional 10-fold intensity drop due to the $I = 9/2$ spin of ^{87}Sr compared with the $I = 0$ for $^{88,86}Sr$. Very substantial improvements in the sensitivity of our apparatus in the years since 1981 now make it possible to see the $^{87}Sr^{19}F$ spectral lines clearly as shown in Fig. V-1. (The principal improvement was due to the use of a large ellipsoid of revolution to collect fluorescence over a 3π solid angle, compared with the limited collecting power of the original lens system). The hfs splittings due to the Sr-centered electron with the ^{87}Sr and ^{19}F nuclear spins are cleanly distinguished. Precise measurements were made for values of the rotational quantum number N from 37 through 75. Both the $A \leftrightarrow X$ and $B \leftrightarrow X$ optical

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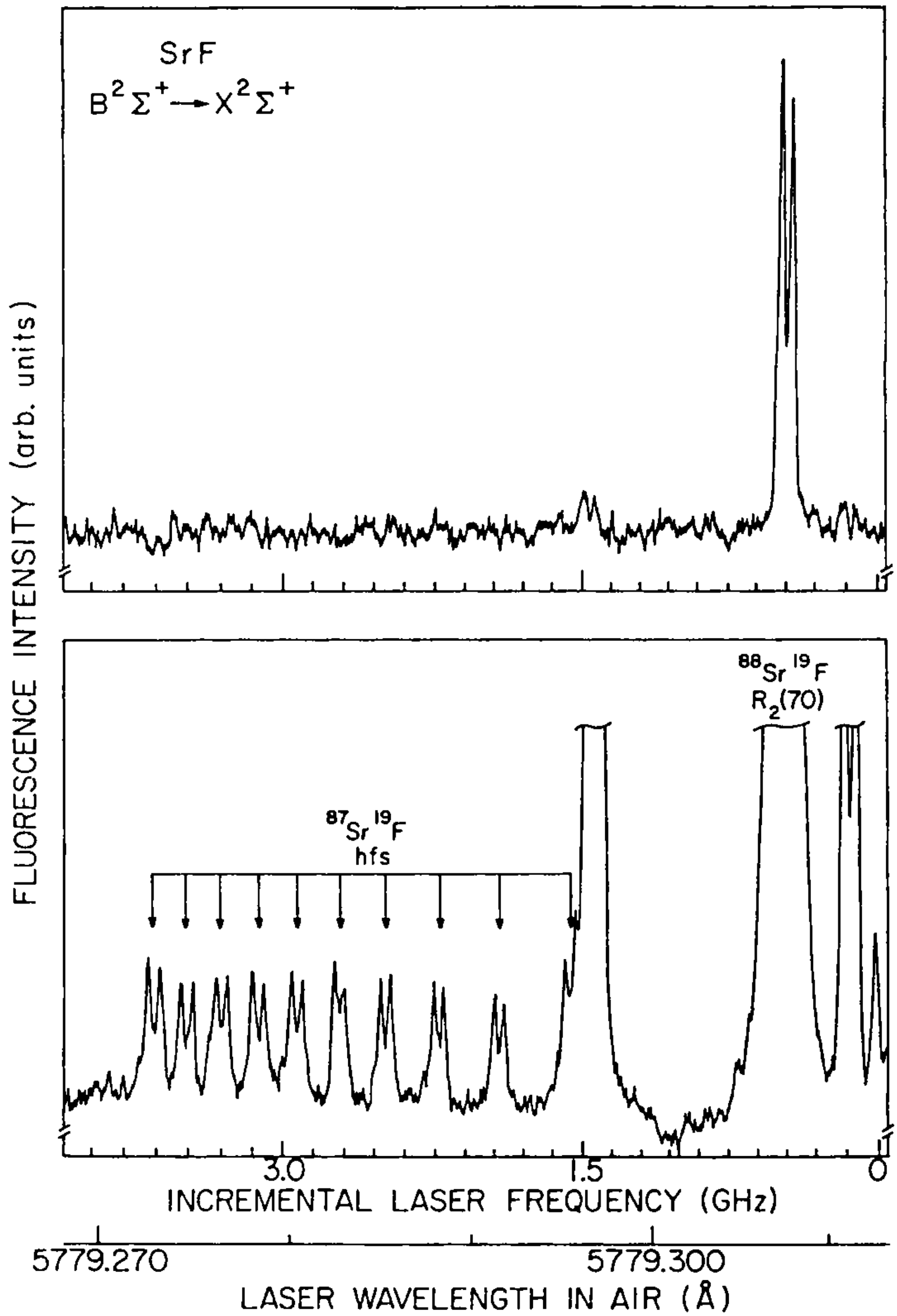

Fig. V-1. (Top) The appearance of a typical molecular line in $^{88}Sr^{19}F$ as seen by laser-induced fluorescence in a molecular beam with a sensitivity characteristic of five years ago. (Bottom) The same region viewed with the newly achieved 100-fold greater sensitivity. The individual hyperfine components associated with the same line in $^{87}Sr^{19}F$ are now clearly visible. Each of the 10 peaks (due top I=9/2 in ^{87}Sr) is split into two by the spin I=1/2 of ^{19}F.

transitions were used in the study. The Hamiltonian previously used to interpret the spin-rotation and hfs interactions within the molecule with only one non-zero nuclear spin was generalized to allow both atoms to have spin. The 10-fold increase in the number of energy levels due to the I=9/2 spin of ^{87}Sr is shown, for a given rovibrational state, in Fig. V-2. Some of the multitude of observable radiofrequency transitions are indicated. An extremely high-quality least-squares fit to all the observations has now been achieved, and the hfs parameters for the ^{87}Sr nucleus obtained for the first time. The values found for the ^{19}F hfs interaction strengths are in excellent agreement with those found previously for ^{86,88}Sr^{19}F. This is the first time the hfs parameters have been measured precisely at both nuclear sites in such a heavy diatomic radical. No evidence for a nuclear spin-spin interaction is found within the 1 ppm experimental precision. Of great interest is the yet-to-be-understood result that ^{87}Sr^{19}F and ^{89}Y^{16}O, while isoelectronic, have opposite signs of the spin-rotation interaction in their $X^2\Sigma^+$ electronic ground states.

d. Spin-Rotation and Hyperfine Interactions in YS
(Y. Azuma and W. J. Childs)

Yttrium monosulfide was studied to assess its similarities to yttrium monoxide (which was studied in detail earlier). In each molecule, the $X^2\Sigma^+$ electronic ground state involves an yttrium-centered electron. Since the hyperfine structure arises from this metal-centered electron interacting with the I = 1/2 yttrium nuclear spin, one would expect the substitution of S for O (on the other end of the molecule) to have a relatively mild effect. A larger difference might be anticipated for the effect on the spin-rotation interaction, however, since it is of a much less localized origin than the hfs. The present double-resonance studies of the groundstate hfs using the B ↔ X optical transitions confirm both of these expectations. The spin-rotation interaction strength γ in the YS ground state is, like that of all diatomics of this class, positive, while that of YO is negative and remains a striking anomaly.

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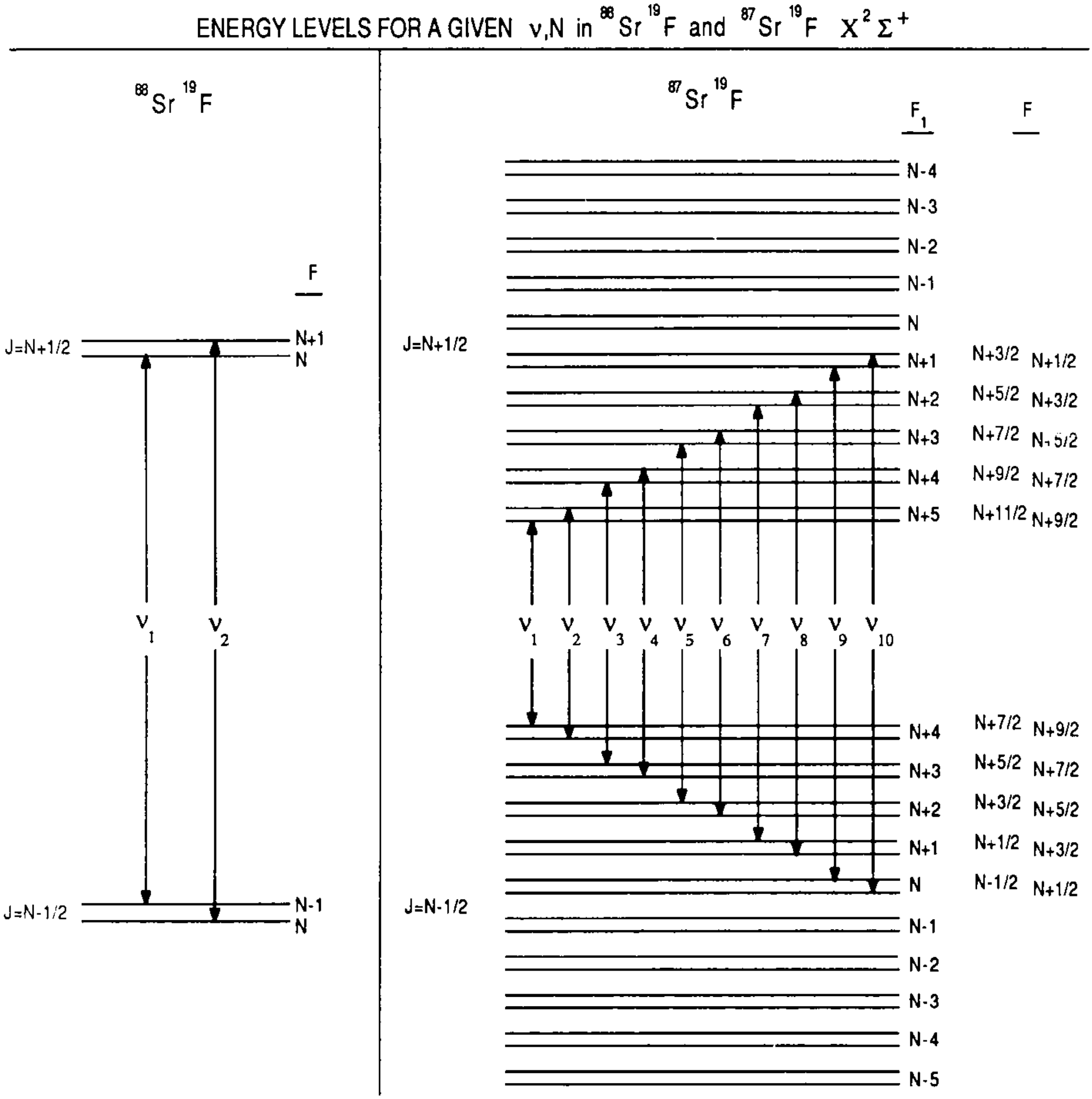

Fig. V-2. Energy levels associated with a single rovibrational state in $^{88}Sr^{19}F$ (at left) and $^{87}Sr^{19}F$ (at right); the additional levels are due to the I=9/2 of ^{87}Sr compared to I=0 of ^{88}Sr. Some of the many observable radiofrequency transitions are indicated.

g. Classification of Closely-Packed Tb I Optical Lines through Lower-State hfs Measurements (W. J. Childs)

The optical spectra of many-electron atoms are typically extremely densely packed and difficult to classify in detail. As an example, the 2-Angstrom region centered on 5441 A in Tb I was known to contain at least 20 distinct spectral lines, each with complex and often overlapping hyperfine structure. Of these, only 5 had been classified at the start of the present experiment and several of the unclassified lines were among the strongest in the region. Since the hfs of nearly all of the 20 lowest Tb I levels is precisely known, it was proposed to use the laser-rf double-resonance method to measure the lower-state hfs of the unclassified lines, and by comparison, identify all those that involve one of these low levels. The results are less satisfactory than might be expected. Although the J-values for 13 of the lower levels were assigned positively, the excitation energies (i.e., the identifications of the levels) could be assigned with certainty in only 5 cases. The spectra remain extremely difficult to assign in detail even in such a limited region and even taking full advantage of the most precise and sophisticated techniques. Lower-state hfs intervals were measured with rf precision for 12 of the transitions, but since the excitation energies associated with the precise hfs splitting information are not known in many cases, the information is of limited usefulness until further work identifies the levels positively.

h. Hyperfine Structure of the Line at 7131.81 A in ^{178}Hf (W. J. Childs and W. Kutschera)

W. Kutschera and collaborators have pointed out the possibility of obtaining an energetic beam of ^{178}Hf ions in the nuclear isomeric state with I = 16, and the exciting research opportunities such a beam could provide. Among the many problems to be overcome would be separating the isomer with spin 16 from the much more abundant nuclear ground state with spin 0. One possibility would be to intersect a very slow, neutral ^{178}Hf beam containing both species with an intense single-frequency cw laser beam to deflect one component of the beam aside leaving only the other. The effective "mass resolution" would depend on the fact that the hyperfine structure for the I = 16 component would be fractionated into several F-levels and shifted from the single component arising from the spin-0 ground state, thereby allowing the laser to interact with only one. The optical transition $5d^2 6s^2$ $^3F_2 \leftrightarrow 5d^2 6s6p$ $^3D_1$ at 7131.81 A is a two-level system so that each atom could absorb (and reemit) many photons successively, always falling back to the initial level. Tuning the laser to the spin-0 component would then drive the ground state beam away, leaving the I = 16 isomeric atoms to continue for beam preparation. Accordingly, the spectral features of this line were recorded with Doppler-free laser fluorescence using an atomic beam of normal isotopic abundances and an orthogonal single-frequency cw laser. The atomic beam, while containing all the stable Hf isotopes, contained no I = 16 isomeric component. The observed isotope shifts and the observed hfs of the odd-A Hf isotopes give considerable hope that the hfs of the isomeric component would be adequate to achieve the separation desired.

VI. FAST ION-BEAM/LASER STUDIES OF ATOMIC AND MOLECULAR STRUCTURE

Our principal goals in this program involve high-precision spectroscopic measurements of structures in ionic species. Experimental studies of this type provide the most stringent tests of *ab initio* calculations of atomic and molecular structure. The BLASE facility provides a well-controlled environment in the production of ions of very well-defined velocities. We take advantage of the speed of the ions to make almost Doppler-free measurements using collinear laser-excitation techniques. The extraction of ions from the discharge ion source and formation into an ion beam provides a collision-free environment.

In the past year we have used the BLASE facility to continue our study of effective two-electron systems. After the initial measurements on Sc II revealed a large (>400%) and systematic discrepancy between *ab initio* theory and experiment, we sought to understand better these results by studying a sequence of homologous ions, starting with Y II. The extremely small hyperfine splitting in this ion required that we use the stimulated-resonance Raman technique which we developed during the previous year. A new, longer optical interaction region designed for such studies was completed, installed and used for the Y II experiments.

During this period, we have also constructed a beamline suitable for laser/ion interaction using beams from the ECR source at ATLAS. This was motivated by a desire to capitalize on the large fluxes of multiply-charged ions produced in highly-excited metastable states by this source. Specifically, helium-like and lithium-like systems are of interest, where accurately measured transition energies can provide stringent tests of QED and relativistic quantum mechanics.

To date, we have measured the energy spread of singly-ionized Ar^+, extracted from the ECR source, by the laser resonance method. Measurements of the Lamb-shift in boron were made in February 1990. The analysis is currently underway.

a. Hyperfine Structure of Y II by Stimulated-Resonance Raman Spectroscopy
(T. P. Dinneen,* N. B. Mansour, C. Kurtz, L. Young, and U. Nielsen†)

We have extended our study of effective two-electron systems from singly-ionized scandium to the homologous yttrium ion. Our earlier work in Sc II revealed major discrepancies between experimental hyperfine structure and standard MCDF calculations. The disagreement was largest for $3d^2$ triplet levels and is presumably due to polarization of the [Ar] core by the two spin-aligned valence electrons. Systematic effects should be apparent by studying the [Kr] core in Y II.

The actual experimental measurement in Y II required the use of the stimulated Raman process, rather than the conventional laser-rf double-resonance method used for Sc II. The reason for this was closely-spaced hyperfine levels arising from the small nuclear magnetic dipole moment in yttrium. During the course of this study we tested the new optical interaction region described in the third technical progress report. A resolution comparable to the laser-rf double resonance method was attained.

Analysis of the resonances observed in four levels of the metastable $4d^2$ configuration ($^3P_{1,2}$;$^1G_4$ and $^1D_2$) required careful accounting of the possible systematic effects due to AC stark shifts in the measurement region. Detailed measurements of resonance width and position were made and compared to a model for coherent population trapping in a true three-level system. An analysis of the relative merits of the stimulated-resonance Raman and the laser-rf double-resonance methods was also made.

The measured hfs intervals in the $4d^2$ configuration in Y II revealed, as in Sc II, a major disagreement with standard *ab initio* MCDF calculations (by U. Nielsen) for the triplet levels. The magnitude of the core polarization contribution has roughly doubled in going from the [Ar] core in Sc^+ to the [Kr] core in Y^+.

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b. Hyperfine Structure in N_2^+
(N. B. Mansour, T. P. Dinneen* and L. Young)

We have undertaken a very high-resolution study of the first negative system of N_2^+ using Doppler-tuned laser fluorescence spectroscopy. As a result, we have fully resolved the hyperfine structure of the light diatomic molecule N_2^+ in the (1,2) vibrational band of the B $^2\Sigma_u^+$ - X $^2\Sigma_g^+$ system for the first time.

In the (1,2) band, we found that the fine structure ordering was sometimes inverted, and that the hyperfine structure was strongly distorted in a flux-rotational state. These observations form solid evidence for the existence of F-dependent perturbations, never before seen in N_2^+. An analysis of these perturbations is currently underway.

In the (0,1) band, our optical measurements are in reasonable agreement with earlier results of Rosner, Gaily and Holt. We expect to improve the results (i.e., remove ambiguities in the fitting procedure) by direct measurements on the X state using the laser-rf double-resonance method between different spin-rotation states. Previous attempts to observe double resonance between neighboring hyperfine levels were unsuccessful due to the small level spacing (<40 MHz).

The results should provide a very sensitive test of molecular wave-function calculations as well as deperturbation methods in a relatively simple, well-studied system.

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c. New/Improved Optical Interaction Region
(C. Kurtz, T. Dinneen* and L. Young)

A new magnetically-shielded optical interaction region was added to BLASE. The design collects light over 30 cm (an order-of-magnitude longer than the previous design). The ion beam passes through one focus of the elliptical tube. Fluorescence emitted from the ion beam is reflected from the polished interior surface of this tube into an adiabatic light guide, which then transports the photons to two photomultiplier tubes (PMT). The tube is made of Cortzar anodized aluminum with ~83% reflectivity. The light guide is fashioned from UV-transmitting acrylic plastic. The overall collection efficiency at the PMT window is estimated to be 60% from 700 to 350 nm. Measurements show the residual magnetic field to be less than 0.05 gauss. The increased optical interaction time provides three advantages: 1) sharper resonances in stimulated-resonance Raman measurements, 2) reduced laser power requirements and hence reduced AC stark shifts, 3) the possibility of measuring excited-state lifetimes shorter than ~1 μs.

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d. ECR Source Energy Spread
(L. Young, T. Dinneen,* N. B. Mansour, C. Kurtz, and R. Pardo)

The precision with which a resonance can be measured in a collinear laser/ion beam experiment is generally governed by the ion source energy spread. We sought to quantify the energy spread of ions produced in an ECR source using the laser resonance method. The laser was swept across the $^4F_{9/2}$ - $^4D^{\circ}_{7/2}$ transition at 6643 Å in singly-ionized argon. Fluorescence from the $^4D_{7/2}$ - $^4P_{5/2}$ transition at 4348 Å was monitored. The measured energy spread varied from 10 to 20 eV over a wide range of source conditions. The addition of He buffer gas to the source improved the beam quality, resulting in a markedly decreased background count rate. Changing the extraction aperture size from 6 mm to 4 mm had little effect on the resonance width.

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This measurement represents the first time the energy spread of ions extracted from an ECR source has been measured using laser techniques. While the technique is not universally applicable, it affords greater precision and selectivity when compared with the conventional magnetic analysis. Indeed, the measurement in Ar^+, represents the velocity spread of a single metastable state located 142187 cm^{-1} above the ground level. It is unclear whether the measured energy spread is more representative of the doubly-ionized Ar ion (which forms the metastable Ar^+ through electron capture) or the singly-ionized Ar ion (which through electron impact excitation could form the metastable Ar^+ state). It may be possible through detailed studies to elucidate population mechanisms in ECR sources.

e. Laser Resonance Measurements in Helium-Like Boron
(T. P. Dinneen*, N. B. Mansour, L. Young, H. G. Berry and R. C. Pardo)

The principal goal in the study of few-electron ions is to achieve, from first principles, a rigorous understanding of relativistic and Lamb-shift effects in strong nuclear Coulomb fields. One way this can be accomplished is by accurate measurements of the QED-sensitive 2^3S - 2^3P transition energies in helium-like systems over a wide range of Z. These transitions have also been the subject of intense theoretical interest. We have chosen to study the helium-like boron system, where the only previous measurement of the 2^3S - 2^3P transitions, in 1934 by Edlén, had an accuracy of only ~ 1.7×10^{-5}. Using the laser resonance method on metastable beams of B^{3+} formed at the ECR source, we expect to be able to improve the accuracy by at least two orders of magnitude (based upon estimates of energy spread from the Ar^+ measurements discussed in d. above.

During an initial run in December 1989, we observed a reproducible resonance on the $2\ ^3S_1$ - $2\ ^3P_2$ transition of approximately 2 GHz width which rose ~2% above background. A complete measurement requires a number of hyperfine components to be found, the smallest of which is only 2.5% the intensity of the largest. A background reduction scheme, based on Doppler-tuning the ion beam (rather than frequency sweeping the doubled-dye laser output), in

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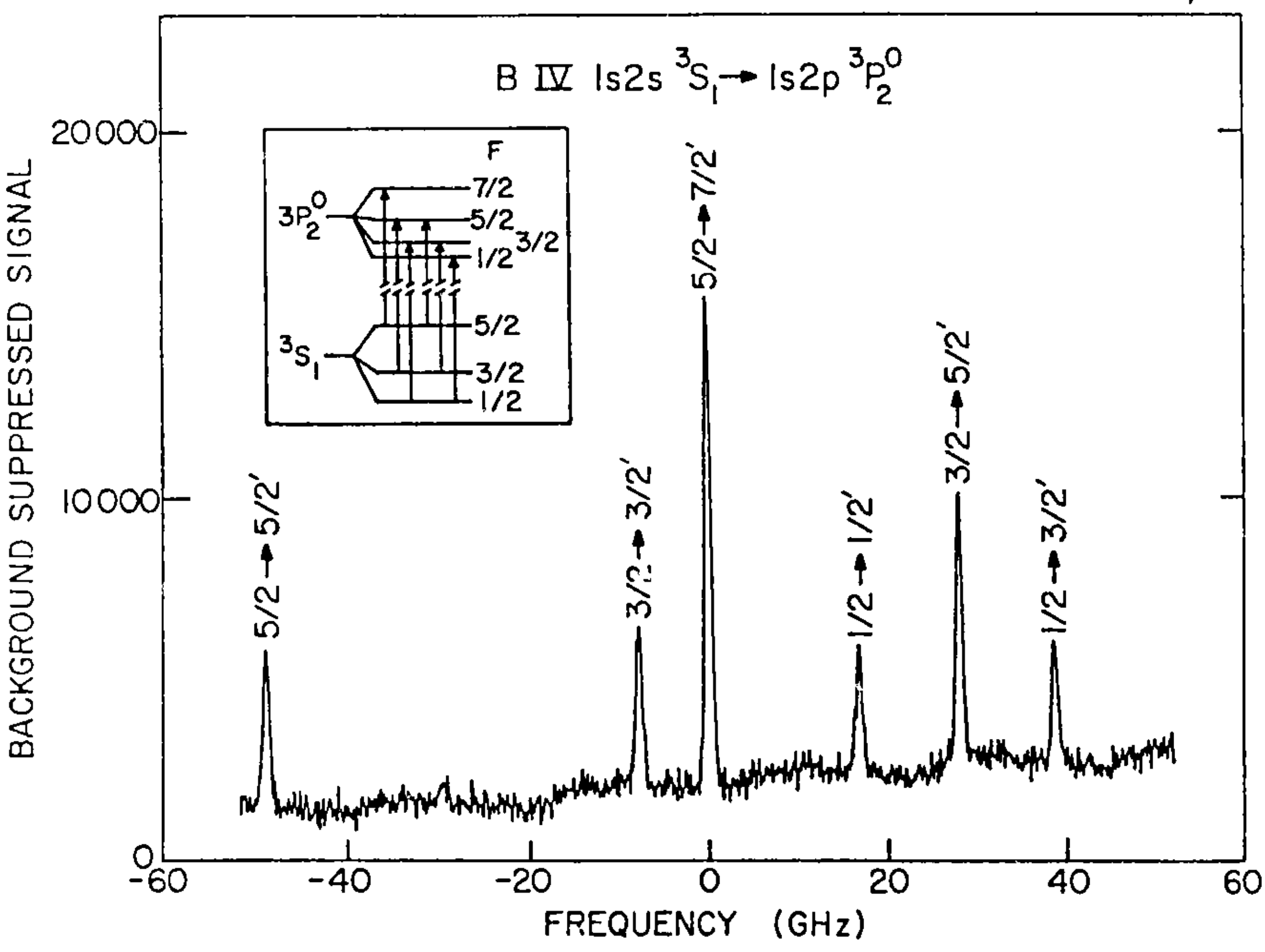

Fig. VI-1. Laser-induced fluorescence signal from a 10-keV He-like boron beam extracted from the ECR source. The laser excites ions in the metastable 1s2s $^3S_1$ state to the 1s2p $^3P_2{}^0$ state and resonance fluorescence back to the $^3S_1$ state is monitored. Hyperfine structure due to the ^{11}B nuclear spin, I = 3/2, is shown in the inset and observed in the spectrum. The actual frequency scan is made by Doppler tuning the ion velocity in the observation region, with the laser frequency fixed.

addition to monitoring the UV laser power, was required for the actual measurement in February 1990 (see Fig. VI-1). A total of 13 hyperfine components (out of 18 possible) were measured, with a relative precision of $\lesssim$50 MHz. Absolute transition energies were determined using a standard iodine reference cell and making "doppler-free" measurements with co- and counter-propagating laser/ion beams. The analysis is currently underway. QED corrections will be measured to a precision better than the best theoretical calculations for this 2s-2p transition.

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

Tightly-collimated beams of molecular ions with energies adjustable in the range 0.5-9.0 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 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 simple, well-known molecular ions (HeH^+, etc.). Even with these, several new and interesting phenomena were 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 has enabled us to measure directly 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 been of significant help to molecular-structure theorists. Work has also continued on producing a very low temperature source for these experiments.

Our effort during FY 1989 was primarily directed toward the study of doubly-charged diatomic molecules and the series of singly-charged carbocations $C_2H_n^+$ (n=1-6). Some of the highlights of this year include:

a. Development of a Segmented-Anode MWPC (SAM)
(A. Belkacem, T. Graber,* E. P. Kanter, R. Mitchell†, Z. Vager, and B. J. Zabransky)

Our experiments with molecules containing protons and two or more heavy ions had previously been severely hampered because of the finite area of the MUPPATS detector. As a result, we had either sacrificed charge-state information (as was the case for $C_2H_3^+$) or information about the proton geometries. This limited our most extensive studies up to now to molecules of the form XH_n^+. Although we could make qualitative statements about the structure of protonated acetylene, we could obtain neither bond length nor vibrational information.[1] For the series $C_3H_n^+$, we were limited to the study of carbon geometries only.[2]

In an effort to alleviate these limitations, we have developed a radically new detector specifically optimized for heavy-ion detection.[3] 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.

During the past year, we completed the implementation of single-wire readout for 288 of the 520 "wires" of the SAM detector. Through careful calibrations of all 576 electronic channels, we have been able to achieve 160 psec time resolution over the entire 276 X 160 mm^2 active area. This has made possible the experiments described below.

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[1]E. P. Kanter, Z. Vager, G. Both, and D. Zajfman, J. Chem. Phys. 85, 7487 (1986).
[2]A. Faibis, E. P. Kanter, L. M. Tack, E. Bakke, and B. J. Zabransky, J. Chem. Phys. 91, 6445 (1987).
[3]A. Belkacem et al., Rev. Sci. Instrum. 61, 2555 (1989).

Concurrent with the detector-development program, improvements in the computer interfacing of the readout electronics and conversion to the DAPHNE data-acquisition system have increased our rate of data collection by more than an order of magnitude. This has been 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 are now able to separate the heavily-ionizing heavy ions from the more weakly-ionizing protons (on the MUPPATS detector) and thus improve the detection efficiencies for molecules containing both types of fragments. Additionally, the large area of the new detector has permitted sufficient electrostatic deflections to resolve heteronuclear heavy-ion fragments (as in the case of our $^{14}N^{15}N^{++}$ data).

b. Measurement of the Bondlengths in Diatomic Dications
(A. Belkacem, E. P. Kanter, R. Mitchell,* Z. Vager, and B. J. Zabransky)

Spectroscopic studies of highly-reactive species, such as molecular ions, are difficult. Nevertheless, there is a rapidly growing body of knowledge on simple singly-charged molecules. However, for multiply-charged molecules, there is little detailed experimental information available, aside from mere proof of existence in mass-spectrometric analyses. For the case of doubly-charged diatomic ions, only a few molecules (such as N_2^{++} and NO^{++}) have been studied. This scarcity of experimental data is in contrast to the important roles such species play in the chemistry of combustion, high-temperature plasmas, and interstellar clouds.

Because Coulomb-explosion imaging utilizes fast beams of isolated gas-phase molecules, it is particularly well suited to studying short-lived or highly-reactive species and during the past year we have applied this technique to several doubly-charged diatomics. In particular, we have studied CO^{++}, CN^{++}, N_2^{++}, NO^{++}, and He_2^{++}. Our results for this latter species were particularly interesting.[1]

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[1]A. Belkacem, E. P. Kanter, R. E. Mitchell, Z. Vager, and B. J. Zabransky, Phys. Rev. Lett. 63, 2555 (1989).

As the isoelectronic analog of the neutral H_2 molecule, the dihelium dication provides an unusual example of the most basic electron-pair bond. We found the measured most-probable bond length to be 0.75±0.02 Å. This value and the shape of the bond-length distribution are, in general, consistent with theoretical predictions of the potential energy surface (see Fig. VII-1).

The cases of the molecules containing heavier atoms (C, N, and O) provide a more stringent test of our model of the Coulomb-explosion process. In order to analyze these data, we conducted a detailed investigation of the charge-state dependence of Coulomb-explosion energies. This study resulted in the development of a model to describe the screened interaction of the ionic fragments during passage through the stripping foil. With this model, we were able to account successfully for the final charge-state and beam-energy dependence of the experimental data and hope to use it to deduce quantitative bond-length information for these heavier systems with the same accuracy obtained for lighter molecules.

c. Stereochemistry of Di-Carbon Carbocations (A. Belkacem, T. Graber,* E. P. Kanter, R. Mitchell,† R. Naaman, Z. Vager, B. J. Zabransky, and D. Zajfman)

The chemistry of hydrocarbon ions in the gas phase is an active field of research not only because of the intrinsic interest in the properties of such molecular ions but also because of their importance in the synthesis of interstellar molecules and in combustion. Such species are present in any hot, reducing gas initially containing stable hydrocarbon molecules. Unfortunately, many of the ions are nonrigid and thus have been difficult candidates for spectroscopic studies.

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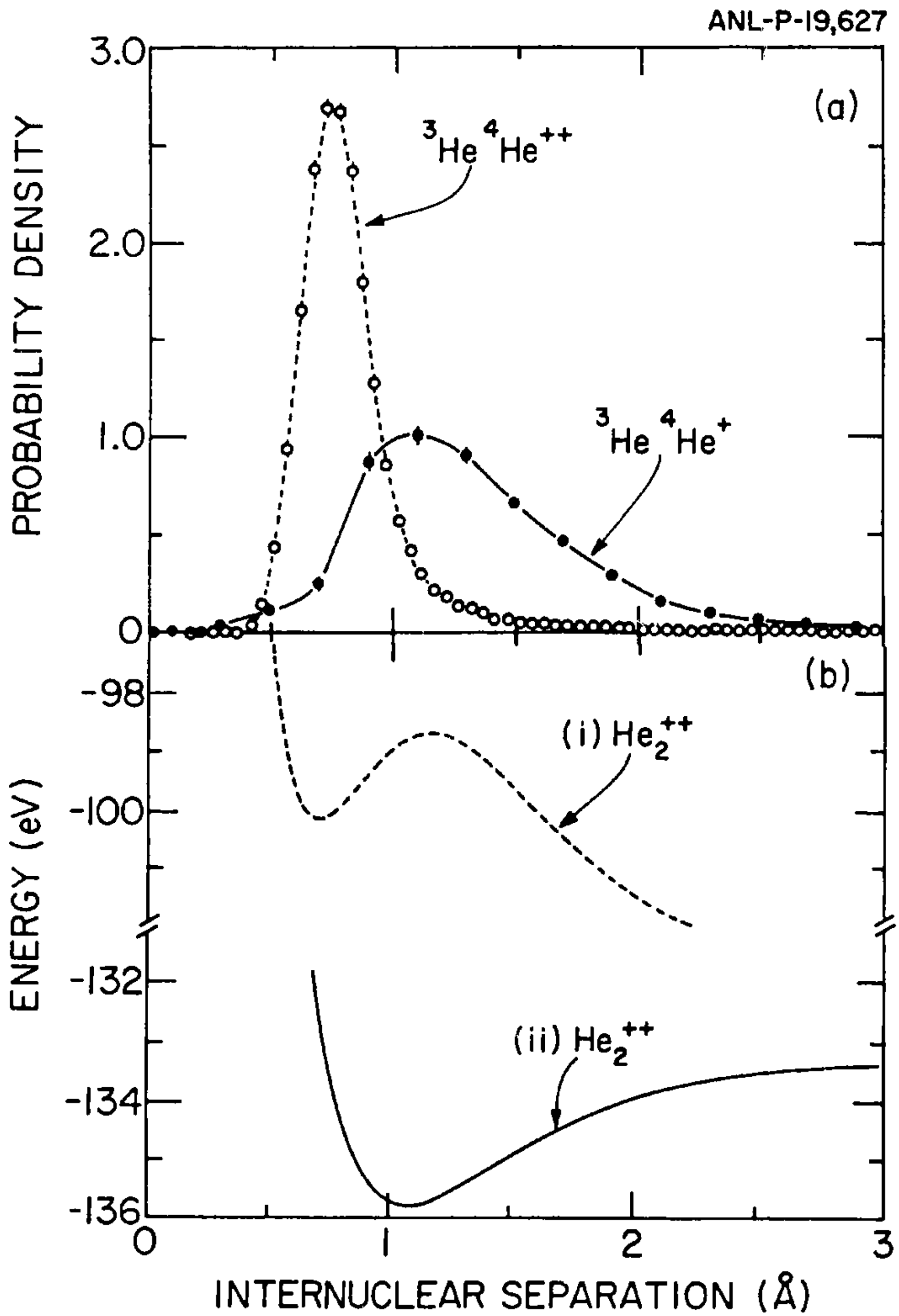

Fig. VII-1. (a) Measured distributions of bond lengths for $^3He^4He^+$ (solid points) and $^3He^4He^{++}$ (open circles). The curves are drawn to guide the eye. (b) Theoretical potential curves for these molecules.

During the past year, we have investigated the structures of the molecules C_2H^+, $C_2H_2^+$, C_2D^+, and $C_2D_2^+$ by Coulomb-explosion imaging. All of these ion beams were formed by low-energy electron impact on acetylene. By reducing the electron impact energy to the threshold for ion production (and decreasing the source-gas density to avoid collisional heating), we have observed comparatively cold ensembles of these species. Indeed the measured widths of the $C_2H_2^+$ H-C-C bending modes approach the predicted frequencies for zero-point vibrations in the ground state.

The equilibrium structures of all of these molecules appear to be linear. However, there are important differences in the vibrational amplitudes. For example, we find the bending modes in C_2H^+ to be much floppier than those in $C_2H_2^+$. For the former, there is a relatively high probability for the hydrogen to penetrate between the two stable linear conformers. For the acetylene cations we find the symmetric bending mode to have a larger amplitude than the antisymmetric motion. The apparently large vibrational amplitudes observed for these molecules are at the present time puzzling and are being studied further.

VIII. THEORETICAL ATOMIC PHYSICS

Our theoretical program in 1989 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. Professor J. Sapirstein of the University of Notre Dame, and Professor L. J. Curtis of the University of Toledo have continued to collaborate with us on the relativistic structures of three-electron systems. The collaborative work is continuing with 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 principally in the theoretical interpretation of measurements in the Coulomb-explosion program.

Professor Peter Sigmund (Odense University) joined us for a sabbatical year in September 1988. He had been appointed an Argonne Fellow for that time. He has begun work on various aspects of the Coulomb-explosion program, and is working on a comprehensive treatise on stopping theory.

a. <u>Barkas Effect in a Dense Medium: Stopping Power and Wake Field</u>
(H. Esbensen and P. Sigmund*)

We have studied the polarization field induced by a heavy charged particle penetrating through a random medium. We have derived a general expression which includes contributions to first and second order in the charge of a particle, and it determines the stopping power up to third order. For a dilute gas, the stopping-power formula reduces to the one that can be derived directly from perturbation theory, applied to an isolated atom or molecule. The interaction between a charged particle and the medium is characterized by two functions, the well-known dielectric functions $\epsilon(k,\omega)$ and a function $Y(k,\omega,k',\omega')$ which depends on two sets of wave number and frequency variables.

We have derived explicit expressions for Y in four different cases: (1) for a random medium of harmonic oscillators from the classical equation of motion, (2) for a classical electron gas from Boltzman's transport equation, (3) for a system of Hartree atoms from quantal perturbation theory, and (4) for the Fermi gas. The different cases yield identical results in those limits where such is to be expected.

In particular, we have evaluated the Barkas effect on the stopping power (to third order in the charge) for a medium of classical harmonic oscillators. The isolated classical oscillator and the classical electron gas emerge from this as simple limiting cases. The classical description applies to distant collisions only.

Quantitative results have been obtained numerically for a quantal electron gas with the Fermi motion disregarded (static electron gas). The results compare well with recent experimental data for proton and anti-proton stopping in silicon. We find that the Barkas correction to the stopping power is mainly positive for positively-charged particles, but it turns negative at low speed, in agreement with existing results for the harmonic oscillator.

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The second-order contribution to the induced field (or wake field) contains a higher harmonic, i.e. a field that oscillates at twice the standard wave number. This alters the wake potential dramatically behind the penetrating particle at low velocities. This effect is possibly an explanation for observed anomalies in molecular-ion energy-loss spectra.

The relative significance of the Barkas correction to the stopping power and the wake field increases with increasing electron density in the medium. This work has been accepted for publication.

b. Stopping Power and Energy-Loss Cross Section of a Point Charge Penetrating Through a Dense Medium of Bound Electrons Particle Stopping (A. Belkacem and P. Sigmund*)

We have derived the dielectric function $\epsilon(\underline{k},\omega)$ in the Lindhard approximation for a medium consisting of electrons individually bound by harmonic forces. The dielectric function is expressible in terms of a hypergeometric series and approaches well-known results in the limits of negligible binding, large momentum transfer, and long wavelength, respectively. The stopping power of a moving-point charge scales very well with the shifted resonance frequency $\alpha_0 = (\omega_0^2 + \omega_p^2)^{1/2}$ (ω_0 = oscillator frequency; ω_p = plasma frequency) that follows from classical dispersion theory. The results differ noticeably from free-electron behavior even at rather high electron density. The discrete excitation levels of an isolated harmonic oscillator are increasingly shifted and broadened with increasing electron density.

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c. Cluster Bombardment (P. Sigmund,* A. Belkacem, and H. Esbensen)

Cluster bombardment of solid targets in the keV/atom energy range leads to several unusual features of the kinematics of recoil events which cannot be found in experiments involving atomic bombarding ions. Mostly qualitative aspects have been explored until now, particularly in relation to some surprising results that we have reported recently. The work is continuing and will be published.

Our theoretical program will continue with a series of visitors until we have sufficient funding for a full-time staff member. We will continue to search for theorists who can directly help our ongoing experimental programs, as well as contribute to the intellectual part of our work, and thus trigger new exciting areas of experimental physics.

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IX. ATOMIC PHYSICS AT ATLAS AND THE ECR SOURCE

The program in atomic physics at ATLAS involves in-house experimenters and collaborations with outside groups. Experiments have included: X-ray and VUV spectroscopy, lifetime measurements, studies of atomic collisions, heavy-ion desorption of biomolecules, Auger electron spectrosopy and studies of Rydberg atoms.

The first stage of the Uranium Upgrade of ATLAS was completed in early 1989. The second stage will be completed in 1990 and the final stage, with extra-low-velocity rf superconducting linac sections will be completed one year later. 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 (the heaviest ion 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 will be accessible from the higher charge states obtained after stripping. Our spectroscopy program is benefitting from our development of a position-sensitive detector in the exit focal plane of the spectrometer.

The atomic physics program has already benefited 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 of such ions. It will be available for atomic physics during periods when it is not being used to inject ATLAS. The ion source was first run successfully in October 1987. The beam line was initially set up in a temporary location in the old West Target Room at ATLAS. Early in FY 1989, the facility was moved to its present 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 typically in the range of 10 to 20 kV.

a. Lifetime of the 2 $^3S_1$ Level in Helium-Like Br^{33+} (R. W. Dunford, D. A. Church, C. J. Liu, H. G. Berry, M. L. A. Raphaelian*, M. Hass†, L. J. Curtis‡)

We have tested the theory of relativistic quantum mechanics by measuring the lifetime of the 2 $^3S_1$ level in helium-like bromine which decays to the ground state via a forbidden M1 transition. We have achieved an accuracy of 3%, which provides a test of the $O(Z^2\alpha^2)$ corrections to the calculations which alter the lifetime by 7%. In our experiment, a beam of bromine ions, which were prepared in the 33+ charge state is incident on a thin carbon target. Some of the ions are excited to the 2 $^3S_1$ level. The decay radiation coming from the beam after passing through the target was observed with two Si(Li) detectors fitted with collimators which allow detection of photons in a 2-mm region along the beam; they have an overall efficiency of about 0.05%. A third, lower-resolution detector which moves with the target is used for normalization. A precision translation device determines the position of the foil to an accuracy of 5 microns (2 $^3S_1$ decay length is about 9 mm). The energy of the beam is measured to 0.1% using the ATLAS time-of-flight energy-measurement system. After correction for energy loss in the foils, the velocity of the beam can be determined to better than 1 percent.

Ground-state decays from the various n=2 levels of helium-like bromine are unresolved in our detectors so the decay curves will be composite. On the other hand, the lifetime of the 2 $^3S_1$ state is almost two orders of magnitude longer than the lifetimes of any of the other levels of Br^{33+} which decay by single-photon emission, so these states are easily eliminated by starting observation sufficiently downbeam of the foil. A major factor contributing to this favorable situation is that both the $^3P_2$ and the $^3P_0$ levels are quenched to the ground state by the hyperfine interaction (I=3/2 for ^{79}Br) which reduces their lifetimes.

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Our measurement yields[1] a lifetime of $\tau^{exp}(2^3S_1)$ = 224.1(7.1) ps which agrees with the theoretical result[2] of $\tau th(2^3S_1)$ = 230 (2) ps. The decay curve is shown in Fig. IX-1. Our experimental error is dominated by uncertainty in the correction for long-lived cascades through the 2p levels which cannot be resolved in our detector. Future progress in this measurement will require the elimination of the cascade problem.

[1]R. W. Dunford, D. A. Church, C. J. Liu, H. G. Berry, M. L. A. Raphaelian, M. Hass, L. J. Curtis, Phys. Rev. A 41, 4109 (1990).
[2]G. W. F. Drake, Phys. Rev. A 3, 908 (1971).

b. Hyperfine Quenching of Forbidden Decays in Helium-Like Ni^{26+}
(R. W. Dunford, C. J. Liu, N. Mansour, R. Vondrasek, J. Last, L. J. Curtis*, and H. G. Berry)

For ions with zero nuclear spin, the 2 $^3P_2$ level in helium-like ions decays to the ground state via M2 radiation or to the 2^3S_1 state via E1 emission. For helium-like nickel the M2 branch (transition rate = 1.2 x 10^{10} s^{-1}) dominates over the E1 branch (transition rate = 2.17 X 10^9 s^{-1}). The theoretical lifetime of this level is 71 ps. In the absence of hyperfine structure the 2 $^3P_0$ level decays only to the 2 $^3S_1$ level via E1 decay. For helium-like nickel, the theoretical lifetime of the 2^3P_0 level is 2.3 ns.

For an ion with nuclear spin, it is expected that the hyperfine interaction will mix 2 $^3P_2$ and 2 $^3P_0$ with the short-lived levels 2 $^3P_1$ and 2 $^1P_1$, thereby altering the lifetimes of these levels. In the case of the longer-lived 2 $^3P_0$ level, an E1 branch to the ground state is opened up and this branch dominates the transition probability.[3] We calculate that the lifetime for the 2 $^3P_0$ level in the isotope $^{61}Ni^{26+}$ (nuclear spin I= 3/2) is 0.45 ns. The shorter-lived 2 $^3P_2$ level is less strongly perturbed by the hyperfine interaction in ^{61}Ni.

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[3]P. J. Mohr in "Beam Foil Spectroscopy, Vol. 1", ed. by I. A. Sellin and D. J. Pegg, (Plenum, New York 1976) p. 97.

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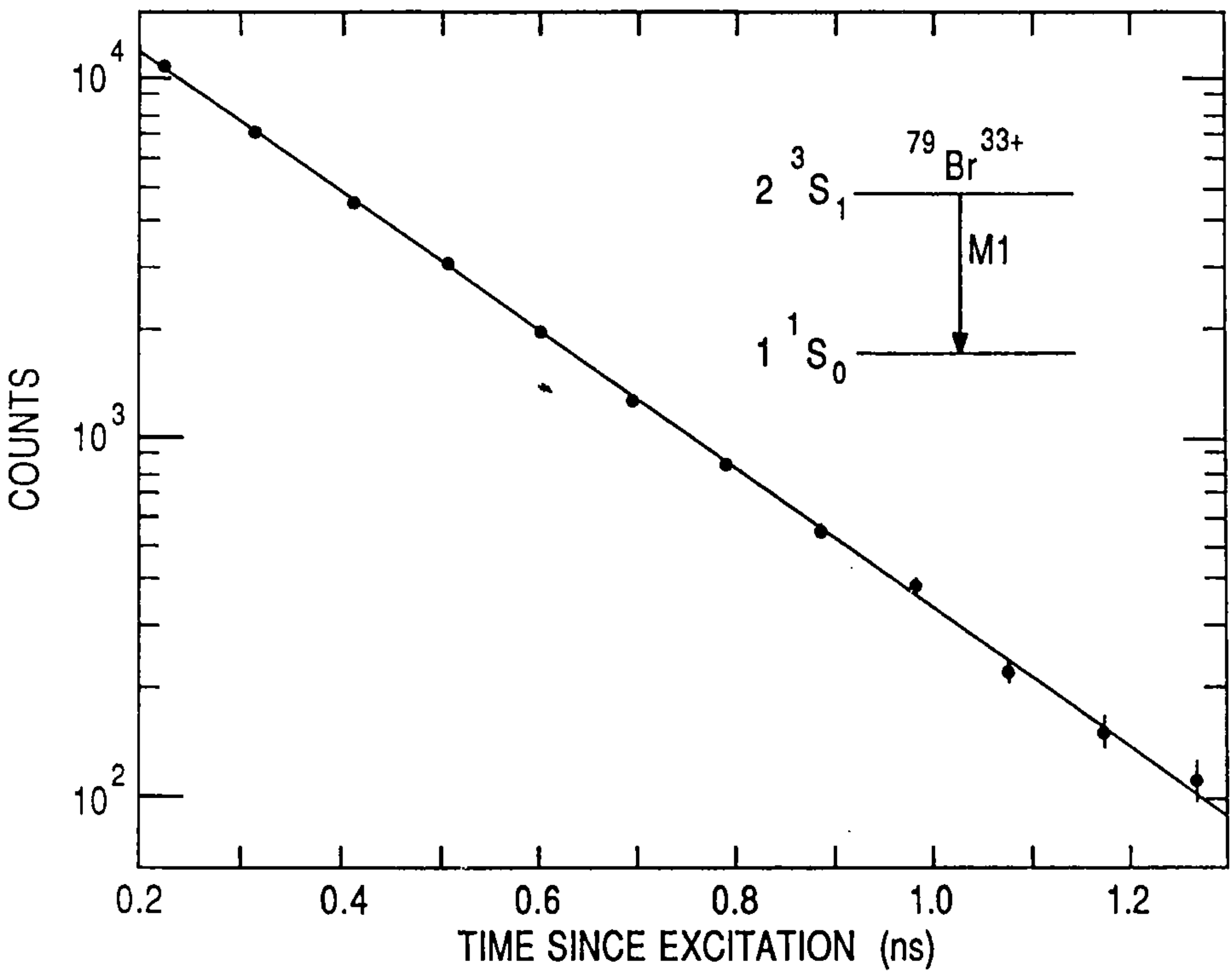

Fig. IX-1. Helium-like bromine decay curve showing data after subtraction of cascade component.

We have measured the lifetime of the 2 $^3P_0$ level in helium-like nickel. By using separated isotopes we compare the lifetime of this state in the isotope ^{58}Ni which has no nuclear spin with the lifetime in the isotope ^{61}Ni which has a nuclear spin of 3/2.

In our experiment, a beam of nickel ions, which have been prepared in the 26^+ charge state, is incident on a thin carbon target. Some of the ions are excited to the 2 $^3P_0$, 2 $^3P_2$ and 2 $^3S_1$ levels. The decay radiation coming from the beam after passing through the target is observed with two Si(Li) detectors. The detectors are fitted with collimators which allow detection of photons in a 5-mm region along the beam; the detectors have an overall efficiency of about 0.1%. The rates in the two detectors are measured as a function of foil-detector separation to determine the lifetime. A third, lower resolution detector which moves with the target is used for normalization. A precision translation device determines the position of the foil. The energy of the beam is measured using the ATLAS time-of-flight energy-measurement system.

Ground-state decays from the various n=2 levels of helium-like nickel are unresolved in our detectors so the decay curves are composites. In the case of ^{58}Ni there is a fast component from the 2 $^3P_2$ decay and a slow component from decay of the 2 $^3S_1$ and 2 $^3P_0$ levels. The decay curve for ^{61}Ni has these two components plus an intermediate component corresponding to the hyperfine quenched 2 $^3P_0$ level. By comparing the decay curves from the ^{61}Ni and ^{58}Ni measurements we have observed directly the hyperfine quenching of the 2^3P_0 level.

c. Polarized Sodium Target (C. J. Liu, R. W. Dunford, Y. Azuma, N. B. Mansour, H. G. Berry, D. A. Church, R. Vondrasek and B. J. Zabransky)

Considerable progress has been made over the past year in the development of our polarized sodium beam target. In off-line studies, a high degree of polarization of the sodium beam was obtained by laser optical pumping. Then the target was placed on one of the two beamlines at the ECR ion source where we produced electron-polarized N^{4+} ions via electron capture of polarized electrons from the sodium. The experiments demonstrate the feasibility of a general method for the production of electron-polarized multi-charged heavy-ion beams. Such beams have important applications in measurements of the hyperfine structure of highly charged ions, tests of quantum electrodynamics and weak interactions (via parity experiments) and studies of spin-dependent effects in the scattering of polarized electrons by polarized ions.

The sodium beam is optically pumped by a CR699-21 ring dye laser. In order to pump both ground-state hyperfine levels (F=2 and F=1) and to cover the complete Doppler profile, we impose both frequency modulation and noise modulation on the laser using two electro-optic modulators. In the off-line studies, the polarization of the target was measured by analyzing the circular polarization of the fluorescence induced by a weak linearly-polarized probe beam and by measuring the ratio of the F=1 to F=2 ground-state hyperfine level populations. These tests indicated that target polarizations greater than 85% could be obtained for a target thickness of 2×10^{10} atoms/cm^2 and laser power density of 600 mW/cm^2.

The electron polarized N^{4+} beam was obtained via electron capture in the polarized target by a N^{5+} beam from the ECR ion source. The polarization of the ions was demonstrated by measuring the circular polarization of the 2s-2p radiation (124 nm) emitted after capture into excited states of N^{4+}. The polarization was analyzed by a polarimeter consisting of a MgF_2 retardation plate, a three-mirror linear polarizer and a channeltron detector. In our first trials[1] a circular polarization of 6% was measured. Theoretical

[1] C. J. Liu, N. B. Mansour, Y. Azuma, H. G. Berry, D. A. Church, R. W. Dunford, Phys. Rev. Lett. 64, 1354 (1990).

calculations indicate that this corresponds to 4% nuclear and electronic polarization for those ions which reach the 2s ground state via this transition.

Our goal is to increase the on-line target polarization significantly and improve the electron polarization of the beam. Our calculations show that with a spinless nucleus, ground-state electron spin polarizations of 25% could be obtained. Our technique for obtaining electron polarization of multiply-charged ions could be applied to the measurement of the hyperfine splitting in the ground state of N^{4+} thus providing a test of the theory of hyperfine structure in lithium-like ions.

d. Measurement of Alignment in Ne^{8+} + Na Collisions
(C. J. Liu, R. W. Dunford, H. G. Berry, Y. Azuma, and N. B. Mansour)

The theory of ion-atom collisions determines the amplitudes for capture into specific levels labelled by a complete set of quantum numbers n, l, and m. Since cross-section measurements give only the n or nl dependence of the the electron capture, information is lost in the sums over the magnetic quantum number m. Sensitivity to the lost information can be obtained by measuring orientation and alignment of the states formed in the collisions. We have studied the alignment of excited Ne^{7+} ions produced in collisions of low-energy Ne^{8+} ions on Na using the sodium beam target. The ions were produced by the ECR ion source. The linear polarization of radiation emitted after electron capture was analyzed using a visible polarimeter. We used interference filters to isolate the 434 nm (n=9 to n=8) transition and the 298 nm (n=8 to n=7) transition in Ne^{7+}.

e. U^{5+} Spectroscopy (D. A. Church, M. Druetta*, C. J. Liu, H. G. Berry, R. W. Dunford and R. C. Pardo)

The first uranium beams were obtained from the ECR ion source in the past year. Using UF_6 as the primary gas and O_2 as the secondary gas, beams of ions up to U^{24+} were obtained with currents larger than 1eμA. Measurable amounts of ions up to U^{32+} were also obtained. We utilized the uranium beams to study electron capture to excited states of francium-like uranium (U^{5+}). Ions of U^{6+} at 0.51 MeV were extracted from the ECR ion source and directed to a H_2 target in the atomic physics beamline. The radiation following capture to excited states of U^{5+} was observed by a normal-incidence UV spectrometer which viewed the interaction region through a 1-mm wide slit in the side of the gas target. We indentified 4 resonance lines in the observed spectrum. A line at 866.7 Å corresponded to the 6d $^2D_{5/2}$-7p $^2P_{3/2}$ transition in francium-like uranium, other transitions observed were: $6d^2D_{3/2}$-$7p^2P_{1/2}$(977.1 Å), $5f^2F_{5/2}$ - 6d $^2D_{3/2}$ (1076.4 Å), and 5f $^2F_{5/2}$-6d $^2D_{3/2}$ (1098.9 Å).

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f. Electron Spectroscopy (M. L. A. Raphaelian,* H. G. Berry, T.J. Gay,† and D. Schneider‡)

a) Saddle-point electrons - H, He,N, Ne on helium targets.

Previous measurements (in 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.

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b) Double-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.

c) 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 spectra 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.

d) 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 with the new Argonne double spectrometer going to higher projectile energies, maintaining the high resolution of the earlier work. Identification of the rich spectrum is in progress. This is aided particulary 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.

g. Positron Production in Heavy-Ion Collisions (R. W. Dunford, APEX collaboration)

We have begun a program at ATLAS to investigate the 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 which will be available after completion of the Uranium Upgrade.

In the past year, the nuclear physics program at DOE has approved a proposal to build a spectrometer suitable for studying the positron peaks. The project is called APEX (ATLAS Positron Experiment). The apparatus will consist of a large weak field Solenoid (300G) which is mounted perpendicular to the beam direction. Electrons and positrons produced at a target at the center of the solenoid undergo helical trajectories and are detected by two thin cylindrical arrays of silicon detectors located at either end of the solenoid. Positrons are identified by their annihilation radiation which is detected by a cylindrical array of NaI detectors. The detectors are shielded from the target by two heavy metal plugs on either side of the target.

The APEX design has been optimized to study the electron-positron coincidence events which have recently been found in the GSI experiments. The total acceptance of our spectrometer for back-to-back e^+e^- coincidences is about a factor-of-four larger than that of the GSI positron experiments. In addition, the apparatus will have an improved capability for measuring the opening angle between the electrons and positrons and thus provide a stringent test of the hypothesis that the coincidences are back to back. Another advantage of the APEX experiment as compared to the GSI positron experirents is that the duty factor of ATLAS is 100% compared to 25% for GSI. This means that if the experiments are limited by instantaneous counting rates, the ATLAS experiment has a factor-of-four advantage.

One of the contributions of the atomic physics group has been in the area of testing targets for the APEX experiment. The targets are tested by measuring the energy loss and straggling of ^{40}Ar ions passing through them. The energy of a 2.5-MeV argon beam produced by the Dynamitron is measured with an electrostatic analyzer after passing through the target. We are able to analyze the initial condition of targets made using different methods (UF_4, U_3O_8, U metal) and then study the stability of the targets after long bombardments.

X. ATOMIC PHYSICS AT SYNCHROTRON LIGHT SOURCES

The broad scientific goals of atomic physics research with X-ray synchrotron radiation include the elucidation of many-body effects such as electron-electron correlations, especially dynamic correlations and the study of relativistic and quantum electrodynamics effects through the investigation of the interaction of X-rays with free atoms, ions and molecules. Also important will be a variety of peripheral interests related to Astrophysics, Chemistry and Solid State Physics.

Our initial studies focus on X-ray photoionization of heavy ions and atoms. Recently, significant progress in this field has been made by a group of researchers, principally from the University of Tennessee (Professor Ivan Sellin) and Texas A&M University (Professor David Church). At Stanford Synchrotron Radiation Laboratory (SSRL), highly-charged rare gas ions, for example Kr^{+9}, were produced at very low recoil energies. In 1988, the group began experiments using the X-26C beam line of the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. We have been part of the collaboration since then.

Our work at the NSLS employs a Penning-type ion trap to store the ions produced by photoionization for subsequent secondary experiments. The Texas A&M group has previous experience on ion-trap work with ions produced by electron impact. Due to the very low recoil energy, the new X-ray photoionization technique produces much cooler ions (the initial temperatures are at least two orders of magnitude smaller). This allows much cleaner trapping geometries, and the cooling of more ions to very low temperatures.

We have succeeded in trapping rare gas ions in a Penning trap with a well depth of 250 mV. Charge-changing collisions between trapped ions and neutral atoms have been studied. Relaxation times of the different charge-state populations can lead to rate coefficients and then to cross sections, once the velocity distributions of the trapped ions have been determined. Also, efforts are being made to study the sequential photoionization of ions to higher charge states.

Our collaboration with the group at the NSLS X-26C has been supported by Argonne National Laboratory Discretionary Funds, as a first step toward an atomic physics program at the APS at Argonne.

Other possible collaborations are also being investigated. The Advanced Light Source (ALS) at Berkeley will be ready for experiments in 1993, two years before the APS.

In FY 1990 we continue to participate in established atomic physics programs at existing light sources. For example, we believe it is beneficial to acquire some experience at higher-energy facilities such as PEP and CHESS where the photon energy is close to that expected from APS. Also, we expect to become involved in work on lower-energy facilities where sophisticated atomic physics experiments are already in progress, such as the SRC at Stoughton, SURF at NIST, the Daresbury Laboratory, SUPER-ACO in Orsay, or DESY in Hamburg.

Overall we see the opportunities at the APS as being linked to the ring's unique characteristics with regard to high energy, low emittance, and fast time structure, which entail possibilities for types of investigations that have hitherto been impossible.

To initiate a national collaborative group of atomic physics users of the Advanced Photon Source at Argonne, as outlined in the document **A Facility for Basic Energy Science Research at the Advanced Photon Source**, we will hold a workshop on March 29 and 30, 1990. The workshop focuses on atomic physics experiments at the APS, and looks closely at opportunities for high-energy X-ray experiments with atoms and ions as well as molecules. We expect to compare the different experimental possibilities for experiments involving ions in traps, in storage rings and from high-intensity ion sources (e.g. an ECR ion source). A variety of relevant subjects such as atomic inner-shell excitation and decay mechanism will be discussed. This workshop is important in deciding future research goals of atomic physics at APS to be undertaken by our group. Plans for establishing a user facility at the APS will be discussed.

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 of the Brookhaven National Synchrotron Light Source took place in August, September and October, 1988 and June 1989. Prior to the runs, several new systems were installed and tested using the Penning-type 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 into 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 in argon, and new results for the rate coefficient of Ar^{6+} in argon. Some results are being analyzed for Ar^{2+} rate coefficients in argon. (ii) Photoionization of Ar^{2+} ions within the trap by the synchrotron photon beam. We studied the photoproduction of Ar^{5+} in this experiment. Only ion signals for charge states greater than 3+ were searched for. A background yield from other charge states was also detected and will be studied further. Also, production and trapping of Xe ions up to charge state +6 has been demonstrated.

*Texas A&M University College Station, TX
†University of Lyon, Lyon, France
‡Brookhaven National Laboratory, Brookhaven, NY
§University of Tennessee, Knoxville, TN

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, who 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)

The atomic physics beam line set up at the ATLAS heavy-ion accelerator continues to be used for a variety of experiments. The beam line has two focussing regions separated by ten meters. A chamber containing an array of four silicon ray detectors and a movable foil target is located at the first focus. An optical encoder has been added to the translation stage so that the position of the movable foil can be precisely determined. 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 split-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 1989 and some of 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, causing delays of several weeks.

ECR Source Beam Lines for Atomic Physics (B. J. Zabransky, R. W. Dunford, M. L. A. Raphaelian* and H. G. Berry)

A switching magnet installed in the ATLAS positive-injection line is used to direct the beam from the ECR source into either of two atomic physics beam lines. The first beam line consists of focussing elements, steerers, slits and diagnostic elements which prepare the beam for the experimental section. The experimental section consists of two 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 monochrometer. The second element in the beam line is a scattering chamber which is used for electron spectroscopy.

The other beam line was constructed in 1989 and contains only one focussing element and experimental section. This beam line is primarily used for laser-ion beam interaction studies and is in close proximity to the lasers and their safety enclosure. The experimental section has a chamber which 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. Both beam lines were used for a variety of experiments in 1989.

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

The BLASE Facility (L. Young, H. G. Berry, C. A. Kurtz, R. L. Amrein and A. E. Ruthenberg)

BLASE is a facility that allows collinear interactions between a fast ion beam and a laser. The ion source is on a stabilized 150-keV platform; ions are analyzed by a 90° magnet.

Experiments on several ions were successfully performed. A new light-collection region an order-of-magnitude longer than previously used was designed and added to the system; it was successfully used with some of the experimental runs. An electro-optic modulator was constructed and used with the laser system allowing control of the overlap between the laser line width and the Doppler spread of the ion beam.

An RF discharge ion source was modified and used for the production of proton beams in conjunction with the polarized sodium-jet experiment. The sodium-jet apparatus was fitted to the end of the BLASE beam line. A microwave source was tested with some success.

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 that 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. A supersonic expansion source is being developed as a source of vibrationally cold molecular ions. It uses an electron gun to ionize molecules emanating from a pulsed nozzle which are then cooled in a supersonic expansion.

Overall, the Dynamitron continued to perform well during the past year. It was scheduled to run experiments for 32 weeks throughout the year. When the machine was not being used for experiments, the technical staff assisted in the construction of beam lines, small accelerators, ion sources and accompished 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 1990. 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 University of N.Y., 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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*No longer at Argonne as of January 7, 1990.
†In charge of ATLAS operations and accelerator development.
‡Resident Associate Guest Appointee.
§Joint appointment with the University of Chicago.
¶ATLAS User Program Administrator.
||On assignment at DOE/HQ until May 31, 1990.

*Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937
*James D. Larson, Ph.D., California Institute of Technoloogy, 1965
*Frank J. Lynch, B.S., University of Chicago, 1944
Thomas Moog, B.A., Princeton University, 1975
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
†John P. Schiffer, Ph.D., Yale University, 1954
Kenneth W. Shepard, Ph.D., Stanford University, 1970
*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
*Jan L. Yntema, Ph.D., Free University of Amsterdam, 1952
Benjamin Zeidman, Ph.D., Washington University, 1957

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*Special Term Appointee.
†Associate Director of the Physics Division. Joint appointment with the University of Chicago.
‡Left the Physics Division in December 1989.
§On assignment at DOE/HQ until October 1990.

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

||Yoshiro Azuma, Ph.D., University of Oregon, 1985
H. Gordon Berry, Ph.D., University of Wisconsin, 1967
**R. Stephen Berry, Ph.D., Harvard University, 1956
††William J. Childs, Ph.D., University of Michigan, 1956
Robert Dunford, Ph.D., University of Michigan, 1978
‡‡Donald S. Gemmell, Ph.D., Australian National University, 1960
Elliot P. Kanter, Ph.D., Rutgers University, 1977
||Noura Mansour, Ph.D., University of Virginia, 1987
‡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
¶¶Joelle Zajfman, M.S., The Technion, Haifa, Israel, 1986

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*Resident Associate Guest Appointee from University of Illinois, Chicago.
†On assignment at Michigan State University through June 1990.
‡Resident Associate Guest Appointee.
§On assignment at the National Science Foundation until January 1991.
¶Special Term Appointee from University of Illinois, Urbana.
||Postdoctoral Appointee until October 1989.
**Special Term Appointee from University of Chicago.
††Retired January 1990. Special Term Appointee as of January 1990.
‡‡Director of the Physics Division.
‡Resident Associate Guest Appointee.
§§Joint Appointment with Weizmann Institute of Science, Rehovot, Israel.
¶¶Special Term Appointee.

TECHNICAL AND ENGINEERING STAFF
(and areas of activity)

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. Ill., 1970). Experimental equipment design.
Jack T. Goral (M.S.M.E. Wroclaw Inst., 1978). Experimental equip. design.
John P. Greene (M.S. DePaul, 1982). Target preparation.
Ray E. Harden (A.A.S. Milwaukee School of Eng., 1957). ATLAS operation.
Dale J. Henderson (B.S. Elmhurst Coll., 1951). Detector development.
James M. Joswick (A.A.S. Milwaukee School 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, ATLAS upgrade.
Floyd Munson, Jr. (A.A.S. DeVry, 1966). ATLAS control system.
Kirt Nakagawa (B.S. Univ. Illinois, 1988). ATLAS operation.
Bruce G. Nardi (A.A.S. DeVry, 1969). Supervisor, electronics maintenance; digital electronics design.
James E. Nelson (B.A. Univ. of Chicago, 1975). Technical assistance, medium-energy physics.
¶John F. Sasso (B.A. Univ. of Chicago, 1987). Computer operations.
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.

¶Joined the Physics Division in February 1990.

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--October 1989)

Ali Belkacem (from University of Lyon, France):
Coulomb-explosion studies.
(September 1987--September 1989)

‡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 Unversity of Iowa, Iowa City, Iowa):
Nuclear theory studies.
(October 1987--October 1989)

Kevin Coulter (from Princeton Unversity, Princeton, New Jersey):
Medium-energy physics.
(December 1988--)

Patricia B. Fernandez (from Univ. of Washington, Seattle, Washington):
Heavy-ion research at ATLAS.
(January 1989--)

Scott Fricke (from University of Minnesota, Minneapolis, Minnesota):
Nuclear theory studies.
(August 1988--)

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*Assistant Director of the Physics Division.
†Joined regular staff in October 1989.
‡Postdoctoral Appointee at Purdue University but resident at Argonne.

Brian K. Fujikawa (from Calif. Inst. of Technology, Pasadena, California):
Weak interactions studies.
(October 1989--)

Ronald Gilman (from Univ. of Pennsylvania, Philadelphia, Pennsylvania):
Medium-energy pion and electron experiments.
(August 1986--August 1989)

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--April 1990)

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--October 1989)

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--)

*Joined regular staff in October 1989.

Craig Roberts (from University of Melbourne, Australia):
Nuclear theory studies.
(July 1989--)

Fernando Scarlassara (from INFN, Padova, Italy):
Heavy-ion research at ATLAS.
(December 1989--)

*Frank L. H. Wolfs (from University of Chicago, Chicago, Illinois):
Heavy-ion research at ATLAS.
(June 1987--)

Alan H. Wuosmaa (from University of Pennsylvania, Philadelphia, Pa):
Heavy-ion research at ATLAS.
(September 1989--)

Daniel Zajfman (from Technion, Haifa, Israel):
Coulomb-explosion studies.
(August 1989--)

Amina Zghiche (from C.E.N., Saclay, France):
Medium-energy research.
(January 1990--)

Long-Term Visitors (at Argonne more than 4 months)

†David A. Church (Texas A & M University, College Station, Texas):
Atomic physics studies.
(January 1989--August 1989)

Joaquim R. Codeco (University of Sao Paulo, Brazil):
ATLAS development.
(August 1989--)

†Edwin Kashy (Michigan State University, E. Lansing, Michigan):
Heavy-ion research at ATLAS)
(August 1989--)

†Karen Kavana (Purdue University, Hammond, Indiana):
Heavy-ion research at ATLAS)
(May 1989--)

*Enrico Fermi Scholar.
†Faculty Research Leave Participant.

*Noemie Koller (Rutgers University, New Brunswick, N.J.):
Heavy-ion research at ATLAS)
(July 1989--)

†Harry J. Lipkin (Weizmann Institute of Science, Rehovot, Israel):
Investigation of current problems in hadron spectroscopy.
(May--August 1989)

Jonhson F. Ordonez (University of Sao Paulo, Brazil):
ATLAS development and construction.
(May 1989--)

‡Peter Sigmund (Odense University, Odense, Denmark):
Particle penetration phenomena.
(September 1988--June 1989)

Juan Jaime Vega (Institute Nacional de Investigationes, Mex. City, Mexico):
FMA development and construction.
(January 1989--December 1989)

Resident Graduate Students

David T. Baran (Northwestern Unviersity, Evanston, Illinois):
Medium-energy nuclear physics studies.
(June 1985-November 1989)

Timothy Dinneen (University of Chicago, Chicago, Illinois):
Laser spectroscopy of fast ions.
(November 1986--)

Timothy J. Graber (Moraine Valley Comm. College, Palos Hills, Illinois):
Coulomb-explosion studies.
(October 1989--)

Michael A. Kroupa (University of Chicago, Chicago, Illinois):
Search for magnetic monopoles using a plastic scintillator array.
(July 1982--)

Mark L. Raphaelian (University of Illinois at Chicago, Illiniois):
Accelerator-based atomic physics.
(January 1987--)

*Faculty Research Leave Participant.
†Joint appointment with Argonne HEP Division.
‡1988-89 Argonne Fellow.

Short-Term Visitors (at Argonne less than 4 months)

A. Faculty

Kevin Beard (University of Notre Dame, Notre Dame, Indiana):
Heavy-ion research at ATLAS.
(November 1989)

Joachim Doehner (University of Heidelberg, W. Germany):
Weak interactions studies.
(November 1989)

Gordon Drake (University of Windsor, Ontario, Canada):
Work at BLASE.
(July 1989)

*Willie J. Gaines, Jr. (Chicago Vocational High School, Chicago, Il.):
Weak interactions studies.
(June-September 1989)

†Edward L. Hohman (York Community High School, Elmhurst, Illinois):
Summer high-school student coordinator.
(June--August 1989)

Hiroshi Ikezoe (JAERI, Tokyo, Japan):
Heavy-ion research at ATLAS.
(May 1989)

Gunther Korschinek (Technical University of Munich, W. Germany):
Heavy-ion research at ATLAS.
(July--October 1989)

Ron Naaman (Weizmann Institute of Science, Rehovot, Israel):
Coulomb-explosion studies.
(August 1989)

Michael Paul (Hebrew University, Jerusalem, Israel):
Heavy-ion research at ATLAS.
(July--August 1989)

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*1989 DOE Teacher Research Associate.
†Guest Faculty Research Participant.

*Akunuri Ramayya (Vanderbilt University, Nashville, Tennessee):
Heavy-ion research at ATLAS.
(May--July 1989)

Oscar Sala (University of Sao Paulo, Brazil):
ATLAS development and construction.
(February 1989)

*Daniel Schlensker (Concordia College, River Forest, Illinois):
Development of 2-MeV Van de Graaff.
(June--August 1989)

*Timothy Steimle (Arizona State University, Tempe, Arizona):
Atomic physics studies.
(July--August 1989)

Michiaki Sugita (JAERI, Tokyo, Japan):
Heavy-ion research at ATLAS.
(May--June 1989)

Yasuharu Sugiyama (JAERI, Tokyo, Japan):
Heavy-ion research at ATLAS.
(August--September 1989)

Hiroyoshi Tanabe (Inst. Kernphysik, University of Mainz, W. Germany):
Nuclear theory studies.
(November 1989)

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*Faculty Research Participant.

B. Graduate Students

*Ian Bearden (Purdue University, W. Lafayette, Indiana):
Heavy-ion research at ATLAS.
(January 1990--)

*John C. Gehring (University of Chicago, Chicago, Illinois):
Heavy-ion research at ATLAS.
(December 1989--)

†Jeffrey Hangst (University of Chicago, Chicago, Illinois):
Ordered ion beams.
(November 1988--)

*David Klepacki (University of Chicago, Chicago, Illinois):
Heavy-ion research at ATLAS.
(September 1988--)

*Zhengtian Lu (University of Chicago, Chicago, Illiinois):
Weak interactions studies.
(October 1989--)

*Madhusree Mukerjee (University of Chicago, Chicago, Illinois):
Nuclear theory studies.
(September 1987--September 1989)

*Ross E. Mitchell (University of Chicago, Chicago, Illinois):
Coulomb-explosion studies.
(February 1988--)

*Thih-Yuen Tung (Northwestern University, Evanston, Illinois):
Nuclear physics experiments.
(September 1987--)

*Danshao Ye (University of Notre Dame, Notre Dame, Indiana):
Heavy-ion research at ATLAS.
(February 1989--)

*Zhou Yu (Northwestern Unviersity, Evanston, Illinois):
Intermediate-energy physics.
(September 1987--)

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*Guest Graduate Student.
†Part-time Graduate Student.

Undergraduate Students

Christopher Batus (College of St. Francis)
John Beacom (University of Kansas)
Jill Brosig (University of Illinois)
Barry Davids (University of Chicago)
Joseph Dey (Washington University)
James Done (Roosevelt University)
Daniel Ehrlich (St. Louis University)
John Gehring (University of Chicago)
Daniel Hernandez (Stanford University)
Randolph Hood (Northwestern University)
Raymond Konopka (Illinois Benedictine College)
Mark Kopciewski (University of Illinois at Chicago)
John Kulpin (Southern Illinois University)
Tina LaGesse (Lewis University)
Thomas Lee (Drake University)
Christopher Legan (Northern Illinois University)
James Magee (Northern Arizona University)
Matthew Marjanovic (Massachusetts Institute of Technology)
Kenneth Manningen (University of Wisconsin)
Patrick Morton (North-Central College)
Michael Nilsson (University of Gottingen, Sweden)
Peter Pashigian (Stanford University)
Gregory Perschbacher (College of St. Francis)
Bonnie Pewitt (University of Kentucky)
Christopher Phelps (Middlebury College)
Robert Rafac (University of Chicago)
Alban Remillieux (ICPI, Lyon France)
Stanley Ridley (Hampton University)
Michael Salisbury (North-Central College)
Derek Schutt (Kalamazoo College)
Savdeep Sethi (Cornell University)
Brett Stevens (University of Chicago)
Jason Stott (Northwestern University)
Phillip Strickhorn (DeVry Institute of Technology)
Richard Vondrasek (University of Chicago)
Eric Weeks (University of Illinois)
Axel Westerlind (University of Lund, Sweden)
Greg Wiemerslage (Elmhurst College)
Kenneth Wharton (Stanford University)
Tammy Wu (Texas A & M University)

Pre-College Program (Just Graduated from High School)
(June--August 1989)

Andrew Grumet (New Trier Township High School)
Martha Natsis (Lyons Township High School)
Lisa Tegeler (Hinsdale South High School)

High School Student Aides
(June--July 1989)

Alban Kellerbauer (Lyons Township High School)
Rebecca Morss (Naperville Central High School)
Sharon Wickboldt (Morton High School West)

National Physical Science Consortium Graduate Fellowship Program
(June--August 1989)

Leslie Lin (Massachusetts Institute of Technology)

PUBLICATIONS FROM 1 APRIL 1989 THROUGH 31 MARCH 1990

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 texts in volumes of proceedings: they are listed chronologically.

Decays of Millisecond Isomers in Odd-Odd N=81 Nuclei ^{146}Tb, ^{148}Ho and ^{150}Tm
R. Broda, P. J. Daly, J. H. McNeill, Z. W. Grabowski, R. V. F. Janssens, R. D. Lawson and D. C. Radford
Z. Phys. A 334, 11-17 (1989)

Fusion of ^{16}O + ^{40}Ca at $E_{lab}(^{16}O)$ = 13.4 MeV/nucleon
C. Beck, D. G. Kovar, S. J. Sanders, B. D. Wilkins, D. J. Henderson, R. V. F. Janssens, W. C. Ma, M. F. Vineyard, T. F. Wang, C. F. Maguire, F. W. Prosser and G. Rosner
Phys. Rev. C 39, 2202 (1989)

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, E. Dafni, K. Beard, U. Garg, P. J. Daly, and M. Piiparinen
Phys. Rev. C 39, 2237 (1989)

Octupole Deformation in ^{223}Ac
I. Ahmad, R. Holzmann, R. V. F. Janssens, P. Dendooven, M. Huyse, G. Reusen, J. Wouters, P. Van Duppen
Nuclear Physics A 505, 257 (1989)

Observation of Superdeformation in ^{191}Hg
E. F. Moore, R. V. F. Janssens, R. R. Chasman, I. Ahmad, T. L. Khoo, F. L. H. Wolfs, D. Ye, K. B. Beard, U. Garg, M. W. Drigert, P. Benet, Z. W. Grabowski, J. A. Cizewski
Phys. Rev. Lett. 63, 360 (1989)

A Calorimeter for Relativistic Heavy-Ion Experiments
D. Beavis, R. R. Betts, M. A. Bloomer, Y. Y. Chu, J. B. Cumming, E. Duek, P. Haustein, I. Juricic, S. Katkoff, and S. B. Kaufman
Nucl. Instrum. Methods A281, 367 (1989)

Binary Decay of ^{56}Ni Formed in the ^{32}S+^{24}Mg Reaction
S. J. Sanders, D. G. Kovar, B. B. Back, C. Beck, D. J. Henderson, R. V. F. Janssens, T. F. Wang, B. D. Wilkins
Phys. Rev. C 40, 2091 (1989)

Recent Developments in the Target Facilities at Argonne National Laboratory
John P. Greene and George E. Thomas
Nucl. Instrum. Methods A282, 191 (1989)

Isotopic Tellurium Targets for Heavy-Ion Nuclear Physics Produced by Vapor Deposition
John P. Greene and George E. Thomas
Nucl. Instrum. Methods A282, 71 (1989)

Gamow-Teller Decay of ^{118}Pd and of Neighbouring Even Isotopes of Palladium
V. Koponen, J. Äystö, J. Honkanen, P. Jauho, H. Penttilä, J. Suhonen, P. Taskinen, K. Rykaczewski, J. Zylicz and C. N. Davids
Z. Phys. A 333, 339 (1989)

Fusion-Evaporation Cross Sections for ^{24}Mg + ^{24}Mg at $5 < E_{lab} < 9$ MeV/Nucleon
F. W. Prosser, S. V. Reinert, D. G. Kovar, G. Rosner, G. S. F. Stephans, J. J. Kolata, C. F. Maguire, Z. Szanto de Toledo, and E. Szanto
Phys. Rev. C 40, 2600 (1989)

A Study of the Electrodisintegration Reaction ^{4}He(e,e'p)^{3}H with Transverse Longitudinal Separation
A. Magnon, M. Bernheim, M. K. Brussel, G. P. Capitani, E. de Sanctis, S. Frullani, F. Garibali, A. Gerard, H. E. Jackson, J. M. Legoff, C. Marchand, Z. E. Meziani, J. Morgenstern, J. Picard, D. Reffay, S. Turck-Chieze, P. Vernin, A. Zghiche
Phys. Lett. B 22, 352 (1989)

Proton Propagation in Nuclei Studied in the A-Dependence of the (e,e'p) Reaction in the Quasifree Region
D. F. Geesaman, R. Gilman, M. C. Green, R. J. Holt, J. P. Schiffer, B. Zeidman, G. Garino, M. Saber, R. E. Segel, E. J. Beise, G. W. Dodson, S. Hoibraten, L. D. Pham, R. P. Redwine, W. W. Sapp, C. F. Williamson, S. A. Wood, N. S. Chant, P. G. Roos, J. D. Silk, M. Deady, and X. K. Maruyama
Phys. Rev. Lett. 63, 734 (1989)

Comment on "Fragmentation of Stretched Spin Strength in ^{28}Si"
Donald F. Geesaman and Benjamin Zeidman
Phy. Rev. Lett. 63, 915 (1989)

Fission in Intermediate Energy Heavy Ion Reactions
J.B. Wilhelmy, M.Begemann-Blaich, T.Blaich, J.Boissevain, M.M.Flower, A.Gavron, B.V.Jacak, P.S.Lysacht, H.C.Britt, D.J.Fields, L.F.Hansen, R.G.Lanier, D.J.Massoletti, M.N.Namboodiri, B.A.Remington, T.C.Sangster, G.L.Struble, M.L. Webb, Y.D.Chan, A.Dacai, A.Harmon, J.Leyba, J.Pouliot, R.G.Stokstad, O.Hansen, M.J.Levine, C.E.Thorn, W.Trautmann, B.Dichter, S.Kaufman, V.Videbaek, Z.Fraenek. G.Mamane, D.Cebra, G.D.Westfall
Nucl. Phys. A502 601c (1989)

Measurement of ^{3}He(n,γ)^{4}He Cross-Section at Thermal Neutron Energies
F. L. H. Wolfs, S. J. Freedman, J. E. Nelson, M. S. Dewey, and G. L. Greene
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Nucleon Alignment in ^{191}Hg: A Competing Mechanism at Moderate Spins
D. Ye, R. V. F. Janssens, M. P. Carpenter, E. F. Moore, I. Ahmad, K. B. Beard, Ph. Benet, M. W. Drigert, U. Garg, Z. W. Grabowski, T. L. Khoo, F. L. H. Wolfs, T. Bengtsson, L. Ragnarsson
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A Superdeformed Band in ^{192}Hg
D. Ye, R. V. F. Janssens, M. P. Carpenter, E. F. Moore, R. R. Chasman, I. Ahmad, K. B. Beard, Ph. Benet, M. W. Drigert, P. B. Fernandez, U. Garg, T. L. Khoo, S. L. Ridley, F. L. H. Wolfs
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Results from the BNL E802 Spectrometer for 14.5 GeV/C per Nucleon Silicon Beams
T. Abbott, E802 collaboration
Nucl. Phys. A 498, 67c-78c (1989)

Search for Short-Lived Axions
Stuart Freedman
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Search for Protons from the D(d,p)T Reaction in an Electrolytic Cell with Pd-Pt Electrodes
K. E. Rehm, W. Kutschera, G. J. Perlow
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Kaon and Pion Production in Central Si+Au Collisions at 14.6 A GeV/c
T. Abbott, E-801 Collaboration
Phys. Rev. Lett. 64, 847 (1990)

Forward-Angle Charged-Pion Electroproduction in the Deuteron
R. Gilman, R. J. Holt, H. E. Jackson, E. Kinney, J. Specht, M. Bernheim, J. Cheminaud, J.-F. Danel, M.-A. Duval, G. Fournier, J.-M. LeGoff, R. Letourneau, A. Magnon, J. Morgenstern, C. Pasquier, J. Picard, D. Poizat, B. Saghai, P. Vernin, M. Brussel, J.-P. Didelez, R. Frascaria, E. Warde, J.-C. Kim
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Bias in Cold Fusion Data
Stuart Freedman and Daniel Krakauer
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Relativistic Calculation of the Deuteron Quadrupole and Magnetic Moments
P. L. Chung, B. D. Keister, F. Coester
Phys. Rev. C 39, 1544 (1989)

Coupled-Channels Calculations for Transfer Reactions
H. Esbensen and S. Landowne
Nucl. Phys. A492, 473 (1989)

Variational Calculations of Drops of Spin-Polarized Liquid ^3He
D. S. Lewart, V. R. Pandharipande and Steven C. Pieper
Phys. Rev. B 40, 712 (1989)

Coupled-Channels Calculations of Elastic and Inelastic Scattering
H. Esbensen and F. Videbaek
Phys. Rev. C 40, 126 (1989)

The Aharonov-Bohm Effect
M. Peshkin and A. Tonomura
Lecture Notes in Physics 340, The Aharonov-Bohm Effect, eds. H. Araki, J. Ehlers, K. Hepp, R. Kippenhahn, D. Ruelle, H. A. Weidenmuller, J. Wess and J. Zittartz (Springer-Verlag Berlin Heidelberg 1989)

Partial-Wave Analysis of the $pp \rightarrow pn\pi^+$ Reaction
T.-S. H. Lee
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Fusion Calculations for $^{40}Ca + ^{40,44,48}Ca$
H. Esbensen, S. H. Fricke, and S. Landowne
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Contribution of Nucleon Transfer to the Elastic Scattering of $^{28}Si+^{58,64}Ni$ Near the Coulomb Barrier
Y. Sugiyama, Y. Tomita, H. Ikezoe, K. Ideno, H. Fujita, T. Sugimitsu, N. Kato, S. Kubono and S. Landowne
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Harry J. Lipkin
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Relativistic Mean Field Theory for Nuclei
A. R. Bodmer and C. E. Price
Nuclear Physics A 505, (1989) 123-144

The Constituent Quark Model Revisited - Masses and Magnetic Moments
Harry J. Lipkin
Phys. Lett. B223, 446 (1989)

Ground State of ^{16}O
Steven C. Pieper, R. B. Wiringa and V. R. Pandharipande
Phys. Rev. Lett. 64, 364 (1990)

Where is the Spin of the Proton?
Harry J. Lipkin
Phys. Lett. B237, 130 (1990)

Experimental Mean-Life Determinations of $2p^5 3p$ and 3d Levels in S VII and Ar IX
M. Westerlind, L. Engstrom, R. Hutton, N. Reistad, S. Bliman,
M. Raphaelian and H. G. Berry
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Z. Vager, R. Naaman, and E. P. Kanter
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Laser-rf Double Resonance Measurements of the Hyperfine Structure in Sc II
N. B. Mansour, T. Dinneen, L. Young and K. T. Cheng
Physical Review A, 39, 5762 (1989)

Lifetimes of Two-Photon-Emitting States in Helium-Like and Hydrogen-Like Nickel
R. W. Dunford, M. Hass, E. Bakke, H. G. Berry, C. J. Liu,
M. L. A. Raphaelian, and L. J. Curtis
Phys. Rev. Lett. 62, 2809 (1989)

Subshell Selective Electron Capture (2-105 keV/amu) Studied by VUV Spectroscopy in O^{6+} + He Collisions
C. J. Liu, R. W. Dunford, H. G. Berry, R. C. Pardo, K. O. Groeneveld,
M. Hass and M. L. A. Raphaelian
J. Phys. B: At. Mol. Opt. Phys. 22, 1217 (1989)

Hyperfine Structure of Some Excited States of $^{133}Cs^+$ by Collinear Laser-Ion Beam Spectroscopy
A. Sen, W. J. Childs
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Polarized Targets for Atomic Physics Experiments with Highly-Charged Ions
R. W. Dunford, C. J. Liu, N. B. Mansour, Y. Azuma, H. G. Berry,
D. A. Church, T. P. Dinneen, L. Young, and B. J. Zabransky
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An Alternative Interpretation of Coulomb Explosion Data on C^+_3
Z. Vager and E. P. Kanter
J. Phys. Chem. 93, 7745 (1989)

Measurement of the Ultrashort Bond Length in He_2^{++}
A. Belkacem, E. P. Kanter, R. E. Mitchell, Z. Vager, and B. J. Zabransky
Phys. Rev. Lett. 63, 2555 (1989)

A High-Resolution Study of Dielectronic Capture by Channeled Ti Ions
A. Belkacem, E. P. Kanter, K. E. Rehm, E. M. Bernstein, M. W. Clark,
S. M. Ferguson, J. A. Tanis, K. H. Berkner, D. Schneider
Phys. Rev. Lett. 64, 380 (1990)

Multiple Scattering of MeV Atomic and Molecular Ions Traversing Ultrathin Films
D. Zajfman, G. Both, E. P. Kanter, and Z. Vager
Phys. Rev. A 41, 2482 (1990)

PAPERS PRESENTED AT MEETINGS

Status of the Positive-Ion Injector for ATLAS
P. K. Den Hartog, R. Benaroya, J. M. Bogaty, L. M. Bollinger, B. E. Clifft, S. L. Craig, D. Henderson, P. Markovich, F. Munson, J. M. Nixon, R. C. Pardo, D. Phillips, K. W. Shepard, I. Tilbrook and G. Zinkann
Proceedings of the 10th International Conference on Application of Accelerators in Industry, Denton, TX, 7-9 November 1988;
Nucl. Instrum. Methods B40/41, 900-903 (1989)

The Argonne Fragment Mass Analyzer
Cary N. Davids and James D. Larson
Proceedings of the 10th International Conference on Application of Accelerators in Industry, Denton, TX, 7-9 November 1988;
Nucl. Instrum. Methods B40/41, 1224 (1989)

Ten Years of Heavy-Ion Acceleration with a Superconducting Linac
Lowell M. Bollinger
Proceedings of the 10th International Conference on Application of Accelerators in Industry, Denton, TX, 7-9 November 1988;
Nucl. Instrum. Methods B40/41, 884-891 (1989)

Order In Cold Ionic Systems: Dynamic Effects
John P. Schiffer
Proceedings of Workshop on Crystalline Ion Beams, Wertheim, FRG, Oct. 4-7, 1988, GSI-89-10 Report, April 1989, ISSN 0171-4546, pg. 2.

Static and Dynamic Properties of Confined, Cold Ion Plasmas: MD Simulations
John P. Schiffer
Book of Abstracts, Yamada Conference XXIV, Strongly Coupled Plasma Physics, Abstract #A5, page 5.

First Operational Tests of the Positive-Ion Injector for ATLAS
L. M. Bollinger, P. K. Den Hartog, R. C. Pardo, K. W. Shepard, R. Benaroya, P. J. Billquist, B. E. Clifft, P. Markovich, F. H. Munson, Jr., J. M. Nixon and G. P. Zinkann
Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, 20-23 March 1989, eds. Floyd Bennett and Joyce Kopta, (IEEE Publishing 1989), 2, 1120-1122 (1989)

The ECR Heavy-Ion Source for ATLAS
R. C. Pardo and P. J. Billquist
Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, 20-23 March 1989, eds. Floyd Bennett and Joyce Kopta, (IEEE Publishing 1989), 1, 319-321 (1989)

The Beam Bunching and Transport System of the Argonne Positive Ion Injector
P. K. Den Hartog, J. M. Bogaty, L. M. Bollinger, B. E. Clifft, R. C. Pardo, K. W. Shepard
Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, 20-23 March 1989, eds. Floyd Bennett and Joyce Kopta, (IEEE Publishing 1989), 1, 545-547 (1989)

A Digital Control System for Accelerator Operator--Host Computer Interface
I. R. Tilbrook
Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, 20-23 March 1989, eds. Floyd Bennett and Joyce Kopta, (IEEE Publishing 1989), 3, 1672-1674 (1989)

A Synchronous Beam Sweeper for Heavy Ions
J. M. Bogaty
Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, 20-23 March 1989, eds. Floyd Bennett and Joyce Kopta, (IEEE Publishing 1989), 1, 595-597 (1989)

An Improved Phase-Control System for Low-Velocity Superconducting Low-Velocity Accelerating Structures
J. M. Bogaty, B. E. Clifft, K. W. Shepard, and G. P. Zinkann
Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, 20-23 March 1989, eds. Floyd Bennett and Joyce Kopta, (IEEE Publishing 1989), 3, 1978-1980 (1989)

Superconducting Low-Velocity Linac for the Argonne Positive-Ion Injector
K. W. Shepard, P. M. Markovich, G. P. Zinkann, B. Clifft and R. Benaroya
Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, 20-23 March 1989, eds. Floyd Bennett and Joyce Kopta, IEEE Publishing 1989, Vol. 2, pp. 974-976

The Liquid Helium System of ATLAS
J. M. Nixon and L. M. Bollinger
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Status of Superconducting RF Cavity Development
K. W. Shepard
Proceedings of the 1989 Particle Accelerator Conference, 20-23 March 1989, Chicago, IL
IEEE Vol. 2, 1764-1768 (1989)

Nuclear Shapes from Spectroscopic Studies of Fission Fragments
I. Ahmad, H. Emling, R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. R. Phillips, and M. W. Drigert
Proceedings of 50 Years with Nuclear Fission, Gaithersburg, MD, 26-28 April, 1989, J. W. Behrens and A. Carlson editors, American Nuclear Society Publishers, 1, 306 (1989)

Measurements of Pulse-Height Defects in Silicon Detectors
D. G. Kovar, S. Desota, B. G. Glagola, D. J. Henderson, R. C. Pardo, B. D. Wilkins, M. A. McMahan, G. J. Wozniak and F. W. Prosser
1989 Spring Meeting of the American Physical Society, Baltimore, MD, 1-4 May 1989; Bull. Am. Phys. Soc. 34, 1174 (1989)

ATLAS Thin-Wire Beam Timing Detector
B. G. Glagola, B. B. Back, L. M. Bollinger, P. K. DenHartog,
D. J. Henderson, D. G. Kovar, R. C. Pardo and B. D. Wilkins
1989 Spring Meeting of the American Physical Society, Baltimore, MD, 1-4 May 1989; Bull. Am. Phys. Soc. 34, 1220 (1989)

Operational Experience of the ATLAS Accelerator
P. K. Den Hartog, J. M. Bogaty, L. M. Bollinger, B. E. Clifft, S. L. Craig,
R. E. Harden, P. Markovich, F. H. Munson, J. M. Nixon, R. C. Pardo,
D. R. Phillips, K. W. Shepard, I. R. Tilbrook, and G. P. Zinkann
5th International Conference on Electrostatic Accelerators and Associated Boosters, Strasbourg, France and Heidelberg, West Germany, 24-30 May 1989; Nucl. Instrum. Methods A287, 235 (1990)

Operational Experience of the ATLAS Accelerator
P. K. Den Hartog, J. M. Bogaty, L. M. Bollinger, B. E. Clifft, S. L. Craig,
R. E. Harden, P. Markovich, F. H. Munson, J. M. Nixon, R. C. Pardo,
D. R. Phillips, K. W. Shepard, I. R. Tilbrook and G. P. Zinkann
5th International Conference on Electrostatic Accelerators and Associated Boosters, Strasbourg, France and Heidelberg, West Germany, 24-30 May 1989; Nucl. Instrum. Methods A287, 235 (1990)

Search for Superdeformation in ^{190}Hg
M. W. Drigert, I. Ahmad, M. P. Carpenter, P. Fernandez, R. V. F. Janssens,
T. L. Khoo, E. F. Moore, F. L. H. Wolfs, D. Ye, K. Beard, U. Garg and
Ph. Benet
American Physical Society Meeting, Washington, D.C., April 16-19, 1990, Bull. Am. Phys. Soc. 35, 1016 (1990)

Study of One- and Two-Particle Transfer Reactions in the System ^{36}S + ^{92}Mo
A. H. Wuosmaa, B. Glagola, T. Happ, W. Kutschera, K. E. Rehm, F. L. H. Wolfs
Spring Meeting of the American Physical Society, April 16-19, 1990, Washington, DC; Bull. Am. Phys. Soc. 35, 998 (1990)

Bunching System for Ions from an ECR Source
R. C. Pardo, J. M. Bogaty, L. M. Bollinger, B. E. Clifft, K. W. Shepard
Spring Meeting of the American Physical Society, April 16-19, 1990, Washington, DC; Bull. Am. Phys. Soc. 35, 958 (1990)

Evidence of Time Delay in the Decay of the Superdeformed Bands of ^{191,192}Hg
M. P. Carpenter, I. Ahmad, P. Fernandez, R. V. F. Janssens, T. L. Khoo,
E. F. Moore, F. L. H. Wolfs, D. Ye, K. B. Beard, U. Garg, M. W. Drigert,
Ph. Benet, J. A. Cizewski
Proceedings of Nuclear Structure in the Nineties, April 23-27, 1990 Oak Ridge, TN, N. R. Johnson editor, 1, 8 (1990)

Level Structure of ^{142}Xe
A. S. Mowbray, M. A. C. Hotchkis, J. L. Durell, J. B. Fitzgerald, W. R. Phillips, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, L. R. Morss, D. Ye, Ph. Benet
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Superdeformation in the A~190 Region
R. V. F. Janssens, I. Ahmad, M. P. Carpenter, R. R. Chasman, P. Fernandez, T. L. Khoo, E. F. Moore, F. L. H. Wolfs, D. Ye, K. B. Beard, U. Garg, M. W. Drigert, Ph. Benet, Z. W. Grabowski
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Structures of Very Neutron-Rich Nuclei ^{104}Zr and ^{103}Zr
I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, L. R. Morss, M. A. C. Hotchkis, J. L. Durell, J. B. Fitzgerald, A. S. Mowbray, W. R. Phillips, Ph. Benet, D. Ye
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Population of Superdeformed Bands, Competition with Fission and Constraints on the Well Depth
T. L. Khoo, R. V. F. Janssens, E. F. Moore, I. Ahmad, M. P. Carpenter, R. R. Chasman, F. L. H. Wolfs, K. B. Beard, D. Ye, U. Garg, Ph. Benet, P. J. Daly, Z. W. Grabowski, M. W. Drigert
Proceedings of Nuclear Structure in the Nineties, April 23-27, 1990 Oak Ridge, TN, N. R. Johnson editor, 1, 26 (1990)

Lifetimes and Side Feeding Times of Superdeformed Bands in Hg Isotopes
E. F. Moore, I. Ahmad, M. P. Carpenter, P. B. Fernandez, R. V. F. Janssens, T. L. Khoo, F. L. H. Wolfs, D. Ye, K. B. Beard, U. Garg, M. W. Drigert, Ph. Benet, Z. W. Grabowski
Proceedings of Nuclear Structure in the Nineties, April 23-27, 1990 Oak Ridge, TN, N. R. Johnson editor, 1, 30 (1990)

Time Evolution of the E2 "Bump" in ^{152}Dy Via a Magnetic Precession Measurement
M. Hass, N. Benczer-Koller, G. Kumbartzki, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, F. L. H. Wolfs, Ph. Benet, K. B. Beard
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