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PHYSICS DIVISION ANNUAL REVIEW

1 April 1987--31 March 1988

Donald S. Gemmell
Division Director

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Edited by Karen J. Thayer

FOREWORD

The Physics Division at Argonne National Laboratory performs basic research in nuclear and atomic physics. The Division, in 1987, had about 110 members (approximately 40 regular scientific [Ph.D. level] staff, 25 postdoctorals and visitors, and 45 technical and secretarial personnel) and an annual operating budget of about \$12 million. The Division's research efforts split approximately into 85% nuclear physics and 15% atomic physics.

Operation of the ATLAS heavy-ion accelerator (a national user facility) and the performance of ATLAS related research, both experimental and theoretical, account for a major fraction of the Division's activities. During 1987 the accelerator was operated on a 5.5 days/week basis. Although this operating schedule was constrained by financial considerations, it did have the benefit that experimenters could usually regain any lost beam time through operation of the accelerator on an overtime basis during weekends. Beam was supplied "on target" for 3612 hours for 44 experiments, 70% of which involved outside users. Membership in the ATLAS users group is currently at the level of 162 scientists from 55 institutions. Of these outside users, 83 participated in experiments at ATLAS during 1987.

The final phase of the BGO gamma-ray facility at ATLAS was completed in August 1987. This device is the result of a very productive collaboration between physicists from Notre Dame University and Argonne. It contains 12 Compton-suppressed germanium detectors and 50 BGO hexagons. It is currently used in about 30% of all ATLAS research. An important recent discovery with this facility is the "superdeformation" in ^{148}Gd , a nucleus that was predicted to have this property based on work in our nuclear theory group. Scientists from the ANL Physics Division are actively collaborating with those from several other institutions in preparing a proposal for a new generation of gamma-ray facility ("Gammisphere") aimed at furthering the broad range of nuclear physics studies that can be undertaken through efficient detection of many coincident gamma rays.

During 1987, we received authorization from the Department of Energy to proceed with the construction of an additional major equipment item at ATLAS, a Fragment Mass Analyzer (FMA). This 20-ton, 8-meter-long recoil-mass-spectrometer will be used to separate nuclear reaction products from the primary heavy-ion beam and disperse them at the focal point according to mass/charge. It will consist of two electrostatic dipoles, four quadrupole singlets, and a magnetic dipole in the symmetric configuration QQEMEQQ. It will have a solid angle of about 8 msr, an energy acceptance of $\pm 15\%$ around the central energy, and an M/Q acceptance of $\pm 3\%$ around the central mass. A workshop was held in September 1987 to discuss the device and the physics program to be performed with it. A steering committee drawn from the ATLAS users community has been formed to assist in the overall guidance of the project. Several tasks in the construction have been assumed by various user groups. The FMA will be housed in a 2700-square-foot extension of the main ATLAS experimental hall. This addition is scheduled for completion in FY1989 and the fragment mass analyzer is expected to be ready for use early in 1990.

The "uranium upgrade" of ATLAS is now well underway and proceeding on schedule. The ECR ion source on its 350-kV platform was brought into operation successfully during the second half of 1987. All four prototypes of the new low- β resonators needed to construct the positive-ion injector linac have been successfully tested. Their performance exceeds the design characteristics by a considerable margin. We confidently expect Phase I of the new injector to be operational early in 1989.

The fact that the ECR source is available upon a high-voltage platform makes it a unique facility for studies in atomic physics. For much of 1988 and (to a lesser extent) of 1989 there will be a "time window" in which the capabilities of this facility will be exploited for atomic physics purposes. To this end, a temporary beam line has been set up and late in 1987 a series of measurements began. This use of the ECR source is symbiotic in the sense that there are substantial benefits also to the nuclear physics program in "debugging", testing, and characterizing the properties of the ion source.

In 1991, we expect to be able to employ ATLAS to accelerate intense high-quality beams of very heavy ions (e.g. uranium) to energies in the region of 5 to 10 MeV per nucleon. It is natural, therefore, to contemplate the use of ATLAS to study the as-yet-unexplained anomalous positron lines that have been observed now for some years at GSI when very heavy ions collide at energies near the Coulomb barrier. The ANL Physics Division ran a conference on the subject of these positron lines in November 1987 and this has been followed up with a series of discussions that will likely culminate in a collaborative proposal to DOE to build an apparatus at ATLAS for the study of these phenomena. Scientists from Yale University, Princeton University, Michigan State University, California Institute of Technology, Florida State University, and Lawrence Livermore Laboratory have all expressed a serious interest in participating in such a collaboration.

Accelerator-mass-spectrometry studies at ATLAS were advanced during 1987 through the extension of the sensitivity in measuring radiocalcium ($^{41}\text{Ca}; T_{1/2} = 100,000$ years) by two orders of magnitude. This has permitted, for the first time, measurements of the $^{41}\text{Ca}/\text{Ca}$ ratio down to levels of $\sim 1 \times 10^{-15}$, a development that was made possible by combining a new method of calcium beam production with a highly selective technique employing a gas-filled Enge split-pole magnetic spectrograph at ATLAS. This development offers fascinating possibilities for paleoanthropological studies.

A recent highlight in our Medium Energy Research Program has been the acquisition of some exciting new results from a collaborative experiment at SLAC where the photodisintegration of the deuteron was measured at several energies in the GeV range. The data show dramatically the transition from an energy regime where a conventional model involving nucleons and pions suffices to describe the data, over to a regime where a description in terms of quarks and gluons is required.

A new initiative involving a collaboration between ANL Physics Division staff and members of the Institute for Nuclear Physics, Novosibirsk is slated to commence early in 1988. This joint effort is aimed at measuring the tensor

analyzing power in electron-deuteron elastic scattering at high momentum transfer. It marries the expertise developed at Argonne in preparing storage cells for polarized atoms with the experience of the Novosibirsk group in storage-ring technology and internal targets.

With current interest in storage rings growing, especially those for cooled ion beams, there is also a heightened interest in the possibilities of observing "crystalline beams", i.e. ordered structures within the cooled circulating ions. Calculations on the properties of such beams are underway in the ANL Physics Division and recently have been extended to include effects that can be expected in actual storage rings (for example "shear" induced by bending magnets, time-dependent focussing, etc.). This work has been encouraged by the recent observation at NBS Boulder of ordered structures in ions stored in a trap.

Highlights of the Atomic Physics Program in the Physics Division over the past year include the start of research programs at two new facilities. Completion of the "BLASE" facility has permitted several high-precision measurements to be made in the field of fast-ion/laser interactions. In addition, as noted above, the ECR ion source constructed as part of the ATLAS upgrade is being used for a series of unique measurements in atomic physics. The first experiments were optical observations of charge-exchange collisions. With the aid of a substantial infusion of Laboratory discretionary funding, the Coulomb-explosion program at the 5-MV Dynamitron accelerator has been able to make significant improvements to the accelerator itself as well as to the beam line and detector systems. Work was begun on determining the structures of some new molecular ions including small carbon clusters. The ion C_3^+ , previously thought to be linear, was shown to be a compact triangular structure. Our work on laser/rf double-resonance spectroscopy has brought new understanding through highly precise measurements of spin rotation and hyperfine interactions in the alkaline-earth monohalides and the group-IIa monoxides.

The following conferences/workshops were organized by our Atomic Physics Group during the past year.

"Opportunities in Atomic Physics Using Slow Highly-charged Ions", Jan. 12-13, 1987.

"Supercomputers in Atomic, Molecular, and Optical Physics", March 16-17, 1987.

"International Symposium on Atomic Spectroscopy in Highly Ionized Atoms", August 15-21, 1987.

In October 1987, Dr. Leonard S. Goodman died quite suddenly after a short illness. Although he had officially retired in 1986, he continued to come to the lab on a regular basis pursuing his goal of precision spectroscopy of excited positronium until the week of his death. His advice and cheerful presence will be greatly missed. He was at Argonne for 40 years, collaborating for much of that time with Dr. William Childs in a series of highly successful and exquisitely precise measurements on magnetic moments and, more lately, in laser/rf double-resonance experiments in atoms and molecules.

In April 1987, Dr. John P. Schiffer, Senior Scientist and Associate Director of the Physics Division was elected to the National Academy of Sciences. This rare honor recognizes John's many contributions to science, particularly nuclear physics, and the substantial impact that he has had in influencing the directions in which nuclear physics has evolved in the past and will develop in the future. We are delighted and proud that his work has been honored in this way.

As has been traditional, the Division had a large influx of visitors including faculty members, graduate students, undergraduate students, and high school students during the summer. We regard this as a very significant part of our activities.

The Annual Review presented here gives a broad, but necessarily incomplete, view of the research activities within the Physics Division for the year ending in March 1988.

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

Donald S. Gemmell
Director, Physics Division

June 1988

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I. RESEARCH AT ATLAS

The heavy-ion research program in the Physics Division at Argonne is conducted with ATLAS, the Argonne Tandem Linac Accelerator System. ATLAS was completed in September 1985, and has been in regular use for experiments. Beam time is allocated with the advice of a Program Advisory Committee and a substantial fraction of experiments (2/3) now involve outside users. Our efforts continue to be divided among several tasks: ongoing research, construction of new apparatus for best usage of the high quality ATLAS beams, and planning for the next generation of experiments, which will take advantage of the improved capabilities made possible by the positive-ion injector upgrade.

The research program addresses a wide range of topics associated with the dynamics of heavy-ion collisions, the structure of nuclei at high spin and temperature, and the interplay between the two. The activities cover several other topics, notably accelerator mass spectrometry and calculation of crystalline structure in cooled heavy-ion beams.

Studies of nuclei at high spin focus on changes of nuclear structure with spin, excitation energy above the yrast line and nucleon number. The experiments investigate nuclear properties both along the yrast line (or in its vicinity) and in the high-lying continuum region. They combine spectroscopy techniques developed for the study of discrete lines with other methods aimed at studying continuous radiation. The excellent resolving power of the BGO gamma-ray facility, which was recently completed, is utilized extensively in these experiments. Evidence was found for superdeformation in ^{148}Gd from the study of the energy correlation between gamma-rays. Dramatic changes along the yrast line and in its vicinity have been observed in ^{154}Dy through identification of levels with spins up to $48\hbar$ and measurements of their lifetimes. Furthermore, studies of the quasicontinuum spectra in this nucleus have revealed the unexpected presence of at least two types of collective motion, the relative importance of which was found to vary with excitation energy and spin. Comparisons with quasicontinuum spectra in the neighboring $^{152-156}\text{Dy}$ nuclei showed how the collective structure above the yrast line varies with neutron number. The study of gamma-rays from a ^{252}Cf fission source continued to delineate a region of octupole shapes at medium spin ($> 7\hbar$) in very neutron-rich nuclei around ^{146}Ba that cannot be produced with reactions. Groups from Notre Dame and Purdue actively participate in these measurements.

The systematic study of quasielastic reactions induced by heavy projectiles has been continued, making use of the heavier beams available from ATLAS and the new focal-plane detector system for the Engle split-pole spectrograph. We are now able to better understand the gross features like energy, mass and projectile dependence of these processes for the simplest one- and two-neutron transfer reactions in terms of a simple semiclassical model.

The interplay between quasielastic reactions, which have surprisingly large cross sections, and other reaction modes (e.g. fusion) was investigated for a variety of systems. It was found that inelastic channels and transfer reactions have to be included in a coupled-channels treatment in order to get a good description of the fusion probability, in particular at low bombarding energies. This particular field benefits from a close collaboration with the Argonne theory group.

From a study of the partition of the reaction cross sections in the systems $Ni + Sn$ and $Se + Pt$ several interesting results were obtained. In the $Ni + Sn$ studies it was found that a substantial fraction of the total reaction cross section is associated with deep-inelastic scattering, even at energies near the barrier. In the $Se + Pt$ study it was found that there are nuclear structure effects present in deep-inelastic reactions. This observation is hard to explain within present theoretical models. A better understanding of this nuclear structure dependence of deep-inelastic reactions and of the energy dependence for these processes, in particular at very low bombarding energies, will be obtained from a study of particle-gamma experiments using part of the BGO setup in conjunction with charged-particle detection with either large-area gas counters or the magnetic spectrograph.

Limitations to fusion arise for heavy systems because of the Coulomb repulsion between the interacting ions which, instead of fusing, reemerge after exchanging nucleons and drifting towards mass symmetry -- a process referred to as quasifission. The characterization of the quasifission process represents a continuing effort at ATLAS. Early theories were based on the assumption that the quasifission process occurs merely as a result of disappearance of the fission barrier in the completely fused system, whereas subsequent models explained the quasifission process as a consequence of the dynamics of the reaction, which inhibits complete fusion for heavy projectiles. Experimental studies at ATLAS, in which the ^{214}Th system was studied via several entrance channels, have shown that there is a strong dependence on the entrance channel mass asymmetry, a result which supports a dynamical description of the quasifission process.

In the measurements of evaporation residues from fusion of heavy ions and lighter targets it has been found that the cross sections increase with energy to a certain point, where saturation is reached, followed by a decrease at even high energies. Work at Argonne has shown that for the $A = 56$ system, fission begins to compete with evaporation at bombarding energies between 2-3 times the Coulomb barrier, which accounts partly for the observed saturation of the cross section.

This finding prompted further studies of this unexpected fission branch of such light systems. These studies have shown that the binary reaction products do indeed display the properties expected for a normal fission decay of a compound system. In further studies of this binary decay, coincidences between the fragments and gamma-rays have been measured using the BGO gamma facility, with the aim of identifying the types of states populated in the fragments.

At high bombarding energies incomplete fusion processes -- where only part of the projectile (or target) fuses -- begin to compete with complete fusion. This process gives rise to reaction products, which are difficult to distinguish from those produced in complete fusion. Work carried out at ATLAS in the last year has sought to distinguish the reaction products arising from complete and incomplete fusion in the $A = 56$ system, and to determine the probability for complete fusion, the decay properties of the compound nucleus, and the mechanism for incomplete fusion. Extensive coincidence measurements between fusion products (evaporation residues and fission fragments) and light charged-particles and between the light particles are being used to discriminate among several models. Groups from Hope College, University of

Kansas, SUNY Stony Brook, Vanderbilt University, and the Weizmann Institute are involved in the ATLAS programs in this area.

A last aspect of the fusion program concerns the decay of the compound nucleus, where we have an on-going systematic study of the shape-relaxation process. The time scale for this relaxation may be 3 orders of magnitude slower than expected, leading to suppression of neutron emission. Experiments to pinpoint the cause of this neutron suppression focussed in the past year on (i) measuring the partial-wave distributions by complementing direct gamma-ray multiplicity measurements with measurements of fusion, fission and transfer cross sections, and (ii) probing the shape of the emitting nucleus through neutron, proton and alpha energy spectra.

Experiments with accelerator mass spectrometry have advanced to detection of the long-lived fission product ^{126}Sn , the heaviest radioisotope measured at ATLAS so far. This was possible through the higher energies from ATLAS and the newly developed technique of a gas-filled spectrograph. Another major effort of AMS is the development of a radiocalcium dating method with ^{41}Ca , a very interesting prospect for paleoanthropology.

Other activities include calculations on several aspects of the possibility of a new condensed crystalline state in cooled heavy-ion beams, nuclear astrophysics measurements on the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ reaction rate -- important for the hot CNO cycle, a measurement of the atomic charge-state dependence of nuclear lifetimes, using the 14-keV state in ^{57}Fe , and planning for experiments to explain the origin of the unexpected, sharp positron-electron peaks seen in heavy-ion scattering experiments at GSI. Several workshops were held to help plan for future experiments with the positive-ion injector upgrade and to solicit input on these experiments and the associated equipment from outside users and experts.

Several design concepts for a detection system for positron-electron coincidences are currently being evaluated, including a new orange-type spectrometer, a time-projection chamber, and a "cruciform" detector.

A major apparatus, the γ -ray facility, was completed in 1987. This apparatus, constructed jointly by Argonne and Notre Dame, consists of 12 Compton-suppressed Ge detectors and 50 BGO hexagons as a sum-energy/multiplicity spectrometer. The capabilities of this facility are already being upgraded by the construction of a scattering chamber which will permit flexible charged-particle- γ coincidences. This chamber will be installed for some experiments in early 1988. The detection system for the Enge split-pole spectrograph has been upgraded to provide good position, timing and Z resolution. A support structure for up to 6 Compton-suppressed Ge detectors to be used for coincidence measurements with the spectrograph has been installed.

Extensive design studies of a Fragment Mass Analyzer were conducted, a design chosen and reviewed, and construction of this device is now underway. With good A/Q resolution (1/300) and very large detection efficiency (up to 40% in some cases), this device will open up many new classes of experiments. Tests will be conducted to determine the feasibility of sustaining the high electric fields which are part of the design.

A new data-acquisition system, based on implementing the DAPHNE program on a micro-VAX computer, has been installed. It will be used for taking data in target Area II, as well as for Target Area III (where it will relieve the heavy load on the present system by permitting more flexibility in testing equipment and in setting up experiments). In addition, it will be used as a play-back station for data analysis.

A. QUASIELASTIC PROCESSES AND STRONGLY-DAMPED COLLISIONS

Based on a systematic study of quasielastic reactions induced by medium-weight projectiles, we are now able to understand better the gross features like energy, mass, and projectile dependence of these processes for the simplest one- and two-neutron transfer reactions. This development was made possible through improvements in detection techniques for heavier projectiles using the Enge split-pole spectrograph and, more recently, the Daresbury recoil mass separator.

The systematic picture which evolved from these measurements can be understood within a simple semiclassical model. This model allows predictions for energy- and angle-integrated cross sections for these processes without having to rely on DWBA calculations. Several recent experiments were devoted to studying possible refinements and extensions of this picture, in particular for proton transfer processes, and for transfer reactions involving deformed or odd-neutron nuclei.

It was shown that for a variety of systems the quasielastic transfer reaction strongly influences, via channel coupling, other reaction modes like fusion reactions, in particular at energies in the vicinity of the barrier. In a new experiment we have studied whether quasielastic neutron reactions are also coupled to strongly-deformed configurations, e.g. in the system $^{48}\text{Ti} + ^{104}\text{Ru}$. In this first experiment no clear signature for this effect was observed.

The availability of heavier beams from ATLAS made it possible to study the partition of the total reaction cross section into the various reaction modes as a function of the neutron number in the systems $^{76,82}\text{Se} + ^{192,198}\text{Pt}$. As in our previous observations in the systems $^{58,64}\text{Ni} + ^{112,124}\text{Sn}$, we found that the quasielastic strength for reactions induced by the most neutron-rich projectiles (^{82}Se , ^{64}Ni) is constant as a function of the mass of the target, while it increases for reactions induced by ^{58}Ni or ^{76}Se . Combined with the measured total reaction cross section it can be concluded that there must be a corresponding neutron-number dependence of the reaction strength for processes associated with more central collisions (mainly deep-inelastic scattering) which is hard to understand within the framework of present macroscopic models.

A better understanding of this nuclear structure dependence of deep-inelastic reactions and of the energy dependence for these processes, in particular at very low bombarding energies, will be obtained from a study of particle-gamma experiments using part of the BGO setup in conjunction with charged-particle detection using either large-area gas counters or the magnetic spectrograph. The necessary hardware for these experiments has been installed and the first measurements are scheduled for spring of 1988.

Several other experiments have been completed during the last year or are in the stage of data analysis. For inelastic scattering of $^{28,30}\text{Si}$ on $^{206,208}\text{Pb}$ an excellent agreement with CCBA calculations was observed, which indicates that the present understanding of these processes is rather detailed. This is not true for the two-particle transfer reactions (^{16}O , ^{14}C) where disagreements between experiment and theory of up to a factor of 700 have been observed from our studies in the system $^{16}\text{O} + ^{90}\text{Zr}$. Although the disparity diminishes at

higher bombarding energies it is not clear whether coupled reaction calculations will be able to improve the situation at the lower energies. An experiment at the borderline between nuclear and atomic physics investigating the dependence of the nuclear lifetime on the atomic charge state in ^{57}Fe has been completed and is presently being analyzed. This experiment which measured charge-changing processes of ^{57}Fe ions traversing the magnetic field of the Enge split-pole spectrograph was made possible through the development of a new focal-plane detector which can determine position, time-of-flight, incident angle, energy and nuclear charge of the ion with very high accuracy.

a. Energy Dependence of the Two-proton Transfer Reaction
 $^{90}\text{Zr}(^{16}\text{O}, ^{14}\text{C})^{92}\text{Mo}$ (K. E. Rehm, B. Glagola, W. C. Ma, F. L. H. Wolfs,
 and W. Phillips*)

We have studied the one- and two-proton stripping reactions $^{90}\text{Zr}(^{16}\text{O}, ^{15}\text{N})^{91}\text{Nb}$ and $^{90}\text{Zr}(^{16}\text{O}, ^{14}\text{C})^{92}\text{Mo}$ at three bombarding energies between 80 and 194 MeV with the Enge split-pole spectrograph. The energy dependence of the cross sections to low-lying states in ^{91}Nb and ^{92}Mo , if compared to theoretical predictions, should give some insight into the question to what extent DWBA and more complicated coupled reaction channels calculations can describe the measured angular distributions for one- and two-proton transfer reactions. The data for the proton transfer channels are analyzed. The cross sections for the two-proton transfer $^{90}\text{Zr}(^{16}\text{O}, ^{14}\text{C})^{92}\text{Mo}(0^+)$ decrease by about a factor of 6 in going from 80-MeV to 194-MeV bombarding energy. For the one-proton transfer reaction the cross sections are well described by DWBA at all bombarding energies. For the two-proton transfer reaction, however, the cross-section ratio between the experimental distribution and the DWBA prediction, assuming a cluster transfer, is 90 at 194 MeV compared to about 700 at 80 MeV. In the future we plan to perform CRC calculations including the $(^{16}\text{O}, ^{15}\text{N})$ reaction as an intermediate step. With these multistep contributions a much better agreement between theory and experiment should be achieved.

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b. Quasielastic Reactions of $^{28,30}\text{Si}$ on $^{206,208}\text{Pb}$ (D. G. Kovar,
K. E. Rehm, J. J. Kolata,* and R. J. Vojtech*)

Quasielastic processes (elastic and inelastic scattering and few-nucleon transfer) have been measured for the systems $^{28}\text{Si} + ^{206,208}\text{Pb}$ and $^{30}\text{Si} + ^{206,208}\text{Pb}$ at $E(\text{Si}) = 8 \text{ MeV/nucleon}$, using the split-pole magnetic spectrometer and its associated focal-plane detector system. The motivation of these experiments was to investigate the extent to which the different nuclear structures of the ^{28}Si and ^{30}Si projectiles influence the various quasielastic reaction channels. The extracted angular distributions for elastic and inelastic scattering were compared with coupled-channel calculations performed with the code PTOLEMY. Good agreement between experiment and theory was observed. The strengths for the neutron transfer reactions, which span a large range in Q-value, were found to be in good agreement with systematics obtained for other neutron transfer reactions induced by medium-weight projectiles. In our continuing study of the energy dependence of various reaction channels in the $^{28}\text{Si} + ^{208}\text{Pb}$ system we have completed the analysis of the data at a bombarding energy of 6 MeV/nucleon. A paper reporting these results has been published. The analysis of an experiment at $E_{\text{lab}} = 5.4 \text{ MeV/nucleon}$ is in progress.

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

The recoil mass separator (RMS) at the Nuclear Structure Facility, Daresbury Laboratory has been used in a novel manner to measure quasielastic reactions at energies below the Coulomb barrier. To date, two series of cross-section measurements have been performed, $^{58}\text{Ni} + \text{Sn}$ and $^{58}\text{Ni} + \text{Sm}$. In the former of these measurements, cross sections for one- and two-neutron pickup reactions were obtained for five target isotopes over a range of bombarding energies from close to the barrier to some 40 MeV below the barrier. These cross sections show an energy dependence which does not depend on the target

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isotope, but a very strong isotopic dependence of the cross-section magnitude. These dependences are understood in terms of the structure of the target and projectile and the variation of the reaction Q-value with target neutron number (see Fig. I-1). The connection between these observations and the dependence of the enhanced sub-barrier fusion of these systems has been investigated and is seen to arise from a coupling between these two reaction channels. In the case of $^{58}\text{Ni} + \text{Sm}$, the reaction Q-values do not depend so systematically on the target isotope and the shape is changing from spherical (^{144}Sm) to well deformed (^{154}Sm). The data for one-neutron pick-up show both changes in energy dependence and absolute magnitude with isotope, the deformed target having a weaker dependence on bombarding energy than expected and by far the largest cross section for sub-barrier transfer. This different behavior from the Sn case and its connection to the apparent deformation dependence of sub-barrier fusion reactions will be investigated in a series of experiments to be carried out at ATLAS this coming year.

In a related experiment we have exploited this technique using the unique combination of the Daresbury Recoil Mass Separator with 16 elements of the Compton-suppressed gamma detector array - POLYTESSA. We have studied the details of final-state population in sub-barrier reactions by detection of the gamma rays in coincidence with target-like recoils (see Fig. I-2). The results for $^{58}\text{Ni} + ^{124}\text{Sn}$ indicate that the dominant reaction mechanism for the one-neutron transfer reaction in this system is by direct transfer, multi-step processes involving inelastic excitation and transfer being much weaker. This information is an essential ingredient in testing the DWBA and CCBA analyses of this reaction and the connection to enhanced sub-barrier fusion. In a future experiment using this technique we will study the final-state population for a series of deformed target nuclei ($^{184,183,182}\text{W}$) in order to test the sensitivity of the one- and two-neutron transfer to details and changes in the structure of these isotopes. In contrast to the Sn case we expect the large deformations of these target nuclei to result in a dominance of the multi-step contribution and thus lead to a sensitivity of the reaction cross sections to transfer matrix elements at high spin.

Fig. I-1. Cross sections for 1-n pickup in $^{58}\text{Ni} + \text{Sn}$ reactions at sub-barrier energies shown plotted versus bombarding energies. The curves through the data are the results of a semi-classical calculation of the transfer probability. Only one overall normalization, to the ^{124}Sn point at the highest energy, is used.

Fig. I-2. Gamma-ray spectra in coincidence with inelastic scattering and transfer of $^{58}\text{Ni} + ^{124}\text{Sn}$ at $E_{\text{cm}} = 150$ MeV. The panels a) and c) show spectra corrected for the Doppler shift corresponding to the Sn ejectile. Panels b) and d) are corrected for emission from the Ni ejectile. The observed transitions are identified.

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

We are investigating if heavy-ion molecular resonance behavior exists in heavier systems. So far the evidence for such behavior has been restricted to relatively light systems with $A < 60$. It is not clear whether this reflects the physics of the process, or the difficulty in obtaining a clear experimental signature in heavier systems where the near-barrier behavior is dominated by the Coulomb interaction. In a recent experiment¹ we measured single-nucleon transfer cross sections for the $^{48}\text{Ti} + ^{104}\text{Ru}$ reaction at $E_{\text{lab}} = 161.8$ MeV to search for a forward-angle enhancement in the reaction yields. Evidence has been found previously in γ -ray studies for superdeformed shapes in the compound system (^{152}Dy) reached by this reaction. Reaction channels which couple to these shapes may experience interaction time delays (resonance-like behavior), which would be revealed experimentally by broadened angular distributions. Although an enhancement is found in the forward-angle ^{49}Ti yields, this enhancement is small and may reflect uncertainties in the analysis. Figure I-3 shows our data along with a DWBA calculation for the $^{104}\text{Ru}(^{48}\text{Ti}, ^{49}\text{Ti})^{103}\text{Ru}$ reaction. We have also looked for increased cross section at forward angles in $^{64}\text{Ni} + ^{92}\text{Zr}$ single nucleon transfer reactions near the barrier--a preliminary analysis failed to show any evidence for an enhancement.

¹S. J. Sanders, B. B. Back, R. R. Betts, D. Henderson, R. V. F. Janssens, K. E. Rehm, and F. Videbaek, Phys. Rev. C 37, 1318 (1988).

- e. Fission and Deep-inelastic Scattering for $^{58}\text{Ni} + \text{Sn}$ at Energies around the Coulomb Barrier (F. L. H. Wolfs)

In order to study the decomposition of the total reaction cross section for heavy-ion reactions at energies around the Coulomb barrier, the fission and deep-inelastic scattering yields for $^{58}\text{Ni} + ^{112,124}\text{Sn}$ have been measured at bombarding energies between 230 and 290 MeV. It is found that at energies below the Coulomb barrier deep-inelastic scattering is an important reaction channel with yields similar to that of fusion. The total reaction cross sections obtained from the elastic scattering angular distributions are now in good agreement with the sum of the measured fission and deep-inelastic scattering yields and the previously measured evaporation and quasielastic cross section. This was part of a thesis project and results are published.

Fig. I-3. Angular distribution for the $^{104}\text{Ru}(^{48}\text{Ti}, ^{49}\text{Ti})^{103}\text{Ru}$ transfer reaction. The curve indicates the calculated DWBA cross sections.

- f. The Transition from Quasielastic to Deep-Inelastic Reaction in the $^{48}\text{Ti} + ^{208}\text{Pb}$ System (K. E. Rehm, A. M. van den Berg, J. J. Kolata,*
D. G. Kovar, W. Kutschera, G. Rosner, G. S. F. Stephans,
and J. L. Yntema)

For the system $^{48}\text{Ti} + ^{208}\text{Pb}$ transfer reactions were measured with single mass and Z-resolution covering the whole energy range from quasielastic to deep-inelastic reactions. The experiment was performed in the Enge split-pole spectrograph with a position-sensitive detector in its focal plane. While the cross sections for transfer reactions are dominated by neutron transfer processes a large number of complex multi-particle exchange reactions have been observed. Wilczynski plots for individual reaction channels could be generated and some results are shown in Fig. I-4. Common to all Wilczynski plots is an orbiting component, i.e. a movement of the angular distributions towards smaller angles with decreasing Q-values (deep-inelastic component). In some cases, in particular for reaction channels in the vicinity of the projectile, one observes an additional contribution which is peaked around the grazing angle and is associated with small Q-values (quasi-elastic component). As can be seen from Fig. I-4 there is no clear difference between these two processes, but rather a gradual transition from one reaction mode to the other. The magnitude of the cross sections and the shape of the Q-value spectra have been analyzed within a simple model which describes the transfer process as a random walk in the N-Z plane and good agreement with the experimental data was achieved. The results have been published recently.

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Fig. I-4. Wilczyński plots for various reaction channels in the $^{48}\text{Ti} + ^{208}\text{Pb}$ system. The outermost contour line corresponds to a cross section of 0.01 mb/(rad.MeV) with an increase by a factor of 10 for each subsequent line. The dashed lines correspond to cross sections of 2 or 5 times the values of the solid lines.

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

In continuation of our studies of the decomposition of the total reaction cross section in the Ni + Sn system at energies around the Coulomb barrier, we have measured the fission and deep-inelastic scattering yields for $^{64}\text{Ni} + ^{112,118,124}\text{Sn}$ using the method of kinematic coincidence with two large-area position-sensitive avalanche counters. From the measured scattering angles and time of flight the masses and energies of the reaction products can be calculated. Since the evaporation of light particles on average does not change the velocity and direction of the reaction products, we can study the primary mass distribution. The results of this measurement together with the results of a previous measurement using ^{58}Ni beams, will allow us to study the energy and neutron dependence of the deep-inelastic scattering yields. The data are completely analyzed and the cross sections are presently being calculated.

From the total kinetic energy of the deep-inelastic scattering products we can conclude that they are emitted from a strongly-deformed system. An experiment to study the decay of these cold and strongly-deformed reaction products in a particle-gamma coincidence is being planned for the summer of 1988.

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

From the analysis of the reaction strength for one-neutron stripping and pickup reactions it was observed that the angle- and energy-integrated cross sections follow a systematic trend, which can be understood in a simple semiclassical model which is based on the Q-matching picture. Using this model it is possible to predict the strength of the one-neutron transfer reactions if the groundstate Q-value and the neutron binding energies in the entrance and exit channels are known. It is therefore not necessary to perform a large number of DWBA calculations in order to get the total energy integrated cross sections. The results have been published. Presently we are investigating if multineutron and charge-transfer processes follow a similar pattern.

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

We have measured angular distributions for one- and two-neutron transfer reactions in the system $^{58}\text{Ni} + ^{232}\text{Th}$ at $E_{\text{Lab}} = 500$ MeV. These measurements were motivated by the observation (obtained in particle-gamma coincidence experiments) that the slope of the angular distributions for two-neutron transfer reactions, if plotted as function of the distance, is similar to the one obtained for the one-neutron transfer reaction whereas, theoretically, one would expect a difference by a factor of two. The measurements were made in the Enge split-pole spectrograph with the new focal-plane counter for particle identification. The data are presently being analyzed.

j. Neutron Transfer Cross Sections Involving Nuclei with Odd Neutron Numbers (K. E. Rehm, I. Ahmad, B. Glagola, W. Kutschera, J. P. Schiffer, T. F. Wang, D. W. Banes,* W. Phillips,* W. Henning†)

The systematics of energy- and angle-integrated one-neutron transfer cross sections (see Section A.h.) predicts too large a cross section for the reaction $^{149}\text{Sm}(^{58}\text{Ni}, ^{59}\text{Ni})^{148}\text{Sm}$ which is the only system studied so far involving a nucleus with an odd neutron number. In order to see if this discrepancy is caused by the neglect of the pairing energy, we have studied the reaction $^{197}\text{Au}(^{57}\text{Fe}, ^{58}\text{Fe})^{196}\text{Au}$, which also involves an unpaired neutron, at a bombarding energy of 340 MeV. The data were measured in the Enge split-pole spectrograph with the new position-sensitive detector (see Section A.j.) in the focal plane. The data are presently being analyzed.

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- k. Elastic and Quasielastic Scattering for $^{76,82}\text{Se} + ^{192,198}\text{Pt}$
(F. L. H. Wolfs, W. C. Ma, K. E. Rehm, 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 been understood yet, but the influence of shell effects for the Ni + Sn system cannot be ruled out. In order to study the dependence of the quasielastic scattering yields on neutron number for a system where shell effects should be minimal, we have measured elastic and quasielastic scattering yields for $^{76,82}\text{Se} + ^{192,198}\text{Pt}$ at 25% above the Coulomb barrier. This measurement showed that the behavior of the total quasielastic scattering yields for the ^{76}Se - and ^{82}Se -induced reactions on Pt is similar to that observed for the ^{58}Ni - and ^{64}Ni -induced reactions on Sn, respectively. The one-neutron transfer cross sections for the Se + Pt reactions can be understood from underlying nuclear structure effects, namely the binding energy of the transferred particle and kinematic matching conditions during transfer. Figure I-5 shows the energy and angle-integrated cross sections together with similar values obtained from other systems (see Sec. A.h). There is a good agreement with the general systematics. To study the decomposition of the total reaction cross section for this system we plan to measure the deep-inelastic scattering and quasi-fission yields in an upcoming experiment.

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

We studied changes in the lifetimes and in the fluorescent yields of excited nuclear states as the charge of the ions is varied. These experiments provide a new way to investigate inner-shell electron properties in stripped atoms, as well as the influence of the electronic environment on nuclear decays.

The first experiments concerned the 14-keV first excited state of ^{57}Fe . A technique was developed to measure the changes in lifetime by using Coulomb excitation in a thin gold target to produce ionic beams of excited $^{57}\text{Fe}^{q+}$.

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Fig. 1-5. Reduced one-neutron transfer cross sections measured for $^{76,82}\text{Se}$ on $^{192,198}\text{Pt}$ (solid points) in comparison with other data involving projectiles between ^{28}Si and ^{64}Ni (Open points) plotted as function of the ground-state Q value.

Each charge-state q is studied in turn by magnetic selection in a split-pole magnetic spectrograph. Ions which enter the magnetic field region in a charge-state q , and undergo no charge-changing process, appear as a peak at the position in the focal plane. Some ions will experience internal conversion decay of the 14-keV nuclear level in the magnetic field region. Their charge will increase by one if the electron hole is filled with accompanying X-rays: if the hole is filled with an accompanying Auger electron, q will increase by two units. Ions resulting from these charge-changing processes will be distributed in the focal plane between the undisturbed charge-state peaks.

In the first measurements it was observed that the structure of the split-pole spectrograph with its gap between the pole pieces is very useful in distinguishing the single and double charge-changing processes. This is because charge-changing processes which occur in the gap result in a peak in the focal plane.

Raytrace calculations, including all charge-changing processes mentioned above, were performed in order to obtain a better understanding of the position spectra measured in the focal plane. It was observed that with an additional measurement of the incident angle and the time of flight through the magnet, all different charge-changing processes should be separable.

In a recent experiment using the new focal-plane detector, which in addition to the magnetic rigidity also measures the time of flight and the incident angle, we have accumulated enough data to obtain a sufficiently accurate lifetime determination. The analysis of this experiment is in progress.

B. FUSION AND FISSION OF HEAVY IONS

The experimental studies of reactions in which substantial rearrangements of the constituents of the interacting nuclei take place, such as complete and incomplete fusion, fission, quasifission and breakup reactions, constitute a major component of the ATLAS experimental program.

The previous observation of a reduction of the number of neutrons emitted from the ^{156}Er compound system when it is formed by fusion of ^{64}Ni and ^{92}Zr , has led to the speculation that the system in this case is temporarily trapped in a superdeformed minimum arising from the shell structure of this system. Several experiments have been carried out, which aim to exclude an alternate explanation of the results in terms of an anomalously large population of high angular momenta in the complete fusion reactions. These experiments appear to exclude this latter explanation.

Studies of the quasifission process, its properties, region of occurrence, and other factors represent an ongoing program at ATLAS. From studies of several reactions, all leading to the compound system ^{214}Th , it has been demonstrated that the occurrence of quasifission is associated with the entrance-channel mass asymmetry in accordance with some theoretical models, rather than the disappearance of the fission barrier of the compound system, as postulated earlier.

The recent discovery of rotational bands associated with so-called superdeformed shapes in the Er-Dy region has triggered a renewed interest in the classical area of superdeformed nuclear shapes, namely the shape isomers in the actinide region. Several experiments have been carried out, which aim to study shape-isomeric states in the actinide region by means of heavy ions.

Considerable experimental effort has been devoted to the study and characterization of two-body breakup of light systems produced in heavy-ion fusion reactions. It has been found that many of the features of such two-body breakup processes are consistent with the normal fission decay of the compound system. This represents a significant advance in the understanding of such processes, which have until recently only been describable by orbiting models based on several arbitrary assumptions.

The study of fusion and incomplete fusion reactions with heavy ions in lighter systems has recently been aided by a significant improvement in measuring techniques. These studies have shown that a substantial fraction of the evaporation residue cross section originates from incomplete fusion reactions, which was misidentified as complete fusion in earlier measurements. These studies are greatly aided by the use of coincidence techniques and time-of-flight measurements using the excellent time structure of the ATLAS beam.

- a. Fission Cross Section in the Fusion of the $^{64}\text{Ni} + ^{92}\text{Zr}$ Reaction
(F. L. H. Wolfs, R. V. F. Janssens, R. Holzmann, W. C. Ma, and S. J. Sanders)

As part of a study to understand the origin of neutron suppression in $^{64}\text{Ni} + ^{92}\text{Zr}$ fusion, we have measured the fission cross section at several energies. These measurements complement the measurements of evaporation residues performed a year ago and together they will provide the total fusion cross section.

The results of the evaporation residue measurement have been published recently. The fission cross sections were measured using the kinematic coincidence technique using two position-sensitive avalanche counters. The masses and energies of the fragments were obtained from the measured scattering angles and flight times.

Beam energies were chosen from 235 MeV (i.e., very close to the Coulomb barrier) to 350 MeV. The target thickness was $70 \mu\text{g}/\text{cm}^2$.

The analysis of the data is still in progress. Preliminary results indicate that the general trend of the data agrees well with that predicted in statistical-model calculations which reproduce the evaporation-residue cross sections. This implies that there is no enhancement of the fission cross section in the vicinity of the Coulomb barrier. The latter would be expected if the l -distribution extended to very high l -values. Thus, our result seems to agree qualitatively with the one derived in an earlier measurement of the l -distribution at the Heidelberg crystal ball. This result, if confirmed in the final analysis, rules out the possibility that the suppressed neutron emission is caused by peculiarities in the total fusion cross section. In order to obtain a complete picture of the distribution of reaction strength for this system, an experiment to study the transfer channels is planned.

- b. Fusion of $^{78}\text{Se} + ^{78}\text{Se}$ and $^{82}\text{Se} + ^{82}\text{Se}$ (R. V. F. Janssens, T. L. Khoo, W. C. Ma, R. Holzmann, M. Quader,* M. Piiparinen,* M. W. Drigert,† and P. J. Daly*)

These measurements are part of a series directed towards understanding the suppression of neutron emission observed in fusion of $^{64}\text{Ni} + ^{92}\text{Zr} \rightarrow ^{156}\text{Er}$ and not seen in fusion of $^{12}\text{C} + ^{144}\text{Sm} \rightarrow ^{156}\text{Er}$. The initial deformation of the system in the early stages of the fusion process is larger in the former case and we have speculated that in the shape relaxation the compound nucleus may be trapped in a superdeformed potential minimum. This theoretically-predicted minimum arises from shell-structure effects and is expected to disappear in Er isotopes as the neutron number increases from 88 to 96. In the reactions $^{78}\text{Se} + ^{78}\text{Se} \rightarrow ^{156}\text{Er}$ and $^{82}\text{Se} + ^{82}\text{Se} \rightarrow ^{164}\text{Er}$, the compound nuclei have these neutron numbers. If trapping in a superdeformed minimum is indeed the cause for neutron suppression, then this suppression should disappear for the latter system.

The channel yields have been measured in the fusion reaction of both systems in order to extract the neutron multiplicity distributions. These can be compared with results from our earlier experiments for ^{156}Er and with published results for $^{160}\text{O} + ^{148}\text{Nd} \rightarrow ^{164}\text{Er}$. Data analysis is now near completion and the major results can be summarized as follows: (i) in the $^{78}\text{Se} + ^{78}\text{Se}$ reaction, the measured neutron multiplicities, as a function of the excitation energy of the compound nucleus, follow a curve very similar to the one observed in the $^{64}\text{Ni} + ^{92}\text{Zr}$ reaction. Thus, the measured neutron multiplicities are lower at all energies than those calculated within the framework of the statistical model. (ii) for the $^{82}\text{Se} + ^{82}\text{Se}$ reaction, several problems with target impurities had impaired the analysis of a first experiment. Data of better quality were recently taken with the BGO γ -ray facility. The analysis of these data has been completed. The neutron multiplicity appears to be somewhat smaller than the one obtained at similar excitation energies in the compound nucleus with the $^{160}\text{O} + ^{148}\text{Nd}$ reaction. Thus, inhibition of neutron emission might be present. However, the l -distribution has to be measured before this statement can be made firmly. Indeed, an l -distribution with tails to high l -values would result in a similar effect.

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- c. Population of Shape Isomers in Heavy-ion Fusion Reactions
(B. B. Back, I. Ahmad, R. R. Betts, C. N. Davids, B. G. Glagola,
R. V. F. Janssens, J. G. Keller, and S. J. Sanders)

The recent discovery of a sequence of γ -ray transitions between the members of a high-spin band of large quadrupole deformation in the $A = 150$ region has attracted much attention to these so-called super-deformed states. Another region of super-deformed states at low spins has, however, been known in the actinide region for many years. These states also have an axis ratio of 2:1 and decay primarily by fission in most cases, hence they are normally known as fission isomers. Fission isomers were originally discovered in heavy-ion induced reactions, but most of the subsequent studies were carried out with beams of light ions and neutrons due to the then widespread availability of such projectiles. As a result of this work, an extensive region of shape-isomers was mapped out in the U - Bk region.

Although a large number of super-deformed shape isomers are known in the actinide region (see Fig. I-6), only very little is known about their excitation spectrum. Two successful studies have been carried out with light-ion beams in the ^{240}Pu and ^{236}U cases, where the rotational bands up to the $I_{\pi} = 8^{+}$ state were identified. These results confirm that the fission isomers are indeed super-deformed states with an axis ratio of approximately 2:1. There are also several cases where an excited state (presumably a spin isomer) decays by fission. Otherwise very little is known about the excitation spectrum of these unusual super-deformed nuclei.

It would therefore be of considerable interest to study the super-deformed bands up to higher spins, which is possible only by means of heavy-ion reactions. Consequently we undertook an exploratory experiment to determine the feasibility of populating and studying actinide shape isomers by means of heavy-ion fusion reactions. If reactions with sufficiently large cross sections for populating the shape isomers were found, it would open the possibility for studying the nuclear structure of these super-deformed states in the actinide region by measuring the γ -rays emitted during the deexcitation in the second minimum. Such future studies would be facilitated by the vast improvement in γ -ray detection techniques which has taken place over the past decade.

Fig. I-6. Presently known fission isomers in the actinide region and their half-lives.

A few studies of fission isomers using heavy ions have been carried out. In bombardments of ^{238}U targets with beams of ^{16}O and ^{22}Ne , Polikanov et al. discovered a short-lived activity, which decayed by fission with a half-life of 14 ms. The cross section for the population of this isomer was of the order $\sim 2 \times 10^{-32} \text{ cm}^2$. The magnitude of this cross section might at first glance discourage further studies of fission isomers using heavy-ion reactions. It was, however, later determined that this isomer belongs to the nucleus ^{242}Am , which can be reached in ^{16}O , $^{22}\text{Ne} + ^{238}\text{U}$ only by very exotic reactions with small cross sections. Later it was shown that fission isomers can be populated in heavy-ion reactions with orders of magnitude larger cross sections if more common exit channels are used. Thus, a cross section of $\sim 0.5 \text{ mb}$ for the population of a 38-ns fission isomer in the $^{12}\text{C} + ^{238}\text{U}$ reaction was found by Bjørnholm, et al. This activity was first assigned to ^{246}Cf , which would be formed via a $(^{12}\text{C}, 4n)$ reaction. Later it was reassigned to ^{243}Cm based on the half-life. This nucleus could be reached by the $(^{12}\text{C}, \alpha 3n)$ reaction. It is, however, not clear which assignment is correct. It is possible that both ^{246}Cf and ^{243}Cm have fission isomers which decay with half-lives in the 40-ns range such that the initial, and more natural assignment of the $^{12}\text{C} + ^{238}\text{U}$ activity, is correct. It was one of the objectives of the present experiment to determine which of these two reactions dominates in order to be able to optimize future studies of the γ -decay pattern in the second well.

We attempted to measure delayed fission activities produced in bombardments of ^{232}Th and ^{238}U targets with 70-MeV ^{12}C beams. The experimental arrangement consisted of two 600-mm² Si detectors facing a $\sim 200\text{mg/cm}^2$ Mylar catcher-foil collecting the recoiling evaporation residues. The Si detectors were operated in singles mode, but kinematical coincidences were also recorded. The distance from the target, which cannot be seen directly by the Si detectors, to the catcher foil was $\sim 2 \text{ cm}$ corresponding to a flight time of $\sim 15 \text{ ns}$. The catcher foil had a hole of 3-mm diameter to minimize interactions between the beam and the catcher foil, which would produce an unwanted background in the detectors. Multiple scattering in the target is estimated to disperse the evaporation residues over an angular range, $\alpha_{1/2} = 15^\circ$ allowing for the majority of the recoils to be deposited on the catcher foil.

In the first measurements, the ~ 38 ns delayed fission activity was produced in the $^{12}\text{C} + ^{238}\text{U}$ reaction utilizing the time structure of the ATLAS beam to identify delayed fission events. The observed counting rate was in agreement with the reported cross section of ~ 0.5 mb.

Secondly, the ^{232}Th target was irradiated in an attempt to determine the prevailing reaction channel for populating the fission isomer. If the $(^{12}\text{C}, 4n)$ reaction dominates we should see the $T_{1/2} = 55$ ns isomer of ^{240}Cm , whereas the 110 ns isomer of ^{237}Pu would be seen if the $(^{12}\text{C}, \alpha 3n)$ is strongest as assumed in the assignment of the 38 ns activity to ^{243}Cm .

The observed counting rate was, however, so low that it was impossible to discriminate between the two half-lives. This fact showed, however, that the hoped-for possibility that the $(^{12}\text{C}, 4n)$ reaction would prevail with a substantially larger cross section did not materialize. The observed counting rate was consistent with a cross section of about 1 mb, rendering the prospects for studying high-spin decays in the second well using this reaction very depressing, indeed.

- d. Measurement of the Shape of the Neutron Spectrum and of the Total γ -ray Spectrum in the Reaction $^{64}\text{Ni} + ^{92}\text{Zr}$ (B. Dichter, R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. Kühn, W. C. Ma, J. J. Kolata,* M. W. Drigert,* M. Quader,† and R. M. Ronningen‡)

As discussed elsewhere in this report, we have strong indications from a series of experiments that the time scale for shape relaxation following fusion may be affected by shell effects and may, in this case, be 3-4 orders of magnitude slower than normally expected. The experimental findings to date are: a) the average n-multiplicity in fusion of $^{64}\text{Ni} + ^{92}\text{Zr}$ is ~ 0.4 smaller than that observed in fusion of $^{12}\text{C} + ^{144}\text{Sm}$ for the same excitation energy in the compound nucleus ^{156}Er ; b) this statement is also true for individual partial waves $\ell > 20 \hbar$; c) the suppression of n-emission is not due to the uncertainties regarding the location of yrast line, the γ -strength function, the neutron kinetic energy or the ℓ -distributions; d) where there is suppression of neutron emission the excess energy is removed by γ -rays, as directly reflected in the measured sum energy. An experiment has been performed to measure the low-energy neutron spectrum for specific channels and the spectrum of γ rays removing the excess energy described in point d).

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Previous work has shown that the spectral shape of low-energy neutrons is particularly sensitive to the location of the yrast line. The spectrum of the γ rays which remove the extra energy can be extracted by measuring and comparing the total γ spectra for the different evaporation residues using the BGO Compton-Suppressed Spectrometers (CSS), in conjunction with the unfolding techniques developed at Argonne.

The analysis of a preliminary measurement has been completed. Neutron spectra were measured at 4 angles (5° , 35° , 55° , 90°) for the reaction $^{64}\text{Ni} + ^{92}\text{Zr}$ at 239 MeV. Background due to scattered neutrons never exceeds 25% for the energies of interest. Calculations with the statistical code CASCADE are currently underway in order to evaluate the extent to which the measured n-spectra can be reproduced.

- e. Study of Fission Fragments from the Reaction $^{32}\text{S} + ^{182}\text{W}$ (B. B. Back, J. G. Keller, B. G. Glagola, S. J. Sanders, F. Videbaek, S. Kaufman, B. D. Wilkins, D. Henderson, and R. Siemssen*)

This experiment is part of a program to study the effects of the entrance-channel mass asymmetry on the binary reaction channels in systems leading to ^{214}Th . Reaction products from the $^{32}\text{S} + ^{182}\text{W}$ reaction were measured in an array of Si detectors over the full angular range from 20° to 160° in the laboratory system. Bombarding energies of 166, 177, 222, and 260 MeV were studied. The product masses were obtained from the combined measurement of energy and velocity of the fragments utilizing the time structure of the beam. A fraction of the coincident fragments were detected in a position-sensitive avalanche detector covering an area of $8 \times 10 \text{ cm}^2$. Total reaction cross sections were derived from an analysis of the simultaneously measured elastic-scattering cross section. The angle-integrated fission cross section is compared with theoretical model predictions based on the proximity potential. A substantial contribution from deeply-inelastic scattering reactions was found at all energies. The fission anisotropies were analyzed in terms of the saddle-point model and they were found to be larger than predicted indicating a contribution of quasifission processes. Also the angular dependence of the average fragment mass shows a small indication of a quasifission contribution (see Fig. I-7). At the two lowest bombarding

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Fig. I-7. Angular dependence of the centroids of the fragment mass distributions are shown for the $^{32}\text{S} + ^{182}\text{W}$ reaction.

energies, $E_{\text{lab}} = 166,177$ MeV, the mass distributions are clearly centered at half the total mass at $A = 1.7$ at all angles, as expected for compound nucleus decay. At the two higher energies, $E_{\text{lab}} = 222,260$ MeV, there appears, however, to be a weak preference for heavier fragments to be emitted at forward angles (and lighter fragments at backward angles). This trend is, however, very weak and may well be of instrumental origin, i.e. inadequate corrections for the energy and time response of Si-detectors to heavy ions. The results of this work have been published.

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

This experiment represents a continuation of the study of entrance-channel effects on binary reaction channels for systems leading to the possible formation of ^{214}Th . In this less-asymmetric system, as compared with the $^{32}\text{S} + ^{182}\text{W}$ reaction, we may expect non-compound nucleus reactions to contribute to the fission-like processes at a measurable level, and provide a determination of the onset of such processes as a function of mass asymmetry. Reaction products emitted in the forward hemisphere were measured in an array of 8 Si detectors for beam energies of 275, 350, 400, 425 MeV. By recording time of flight of the reaction products relative to the beam timing, it is possible to determine both mass and energy of the products. From a preliminary analysis of the data it appears that a strong component of deep-inelastic scattering occurs for the two highest energies. The elastic scattering, deeply-inelastic scattering and fission-like components of the total reaction cross section will be analyzed and compared to the prediction of theoretical models. In the $^{60}\text{Ni} + ^{154}\text{Sm}$ reaction we observe a strong component of non-compound fission-like reaction products. In Fig. I-8 we show the angular distributions for fragments belonging to different mass bins for the beam energy of $E_{\text{lab}} = 339$ MeV. The mass bin $A = 106-110$ corresponding to symmetric mass splits is strictly forward-backward symmetric as required for binary exit channels. Going to lighter fragment masses we find a progressively stronger preference for emission at forward angles. This behavior is inconsistent with the binary decay of a compound system and it shows that the reaction time is shorter or comparable to the rotational period

Fig. I-8. Angular distributions for fragments falling into different mass bins are shown for the $^{60}\text{Ni} + ^{154}\text{Sm}$ reaction at $E_{\text{lab}} = 339 \text{ MeV}$. The solid points are data for the mass bin indicated in the figure. Open circles correspond to the complementary fragment plotted at the supplementary angle.

of the interaction complex. The solid curves are calculated on the basis of the standard formalism for fission angular distributions. The angular asymmetry is achieved by multiplying the standard expression with an exponential function such that the full expression is

$$W(\theta) = \sum_{I=0}^{\infty} (2I+1) P(I) \exp[\beta(\theta - \frac{\pi}{2})] \sum_{k=-I}^I \frac{1}{2} (2I+1) \rho(K) |d_{0,K}^I(\theta)|^2 \quad (2)$$

where $P(I)$ is the partial wave distribution, β is a parameter controlling the angular asymmetry, $\rho(K)$ is the K -distribution (K is the axial component of total spin I) and $d_{0,K}^I(\theta)$ is the θ -dependent part of the symmetric top wave function. The partial wave distribution $P(I)$ is taken from model calculations which reproduce the excitation function for fission-like processes whereas the K_0^2 value (the variance of the Gaussian K -distribution, $\rho(K)$ is obtained from a fit to the angular distribution for the $A = 46-50$ mass bin. The solid curves for the other mass bins are obtained by adjusting the slope parameter β and the overall normalization. We observe that this single choice for the K_0^2 -value gives a good representation of the data for all mass bins. This indicates that, within the experimental sensitivity, the variance of the K -distribution is not strongly dependent on the mass split in the process. These data are, however, not sufficiently accurate in the extreme forward region to rule out a weak mass dependence of the K_0^2 value as observed in the ^{50}Ti , $^{56}\text{Fe} + ^{208}\text{Pb}$ reactions by Kratz et al. A manuscript describing the results of this experiment is being prepared for publication.

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

This experiment is part of the study of entrance-channel effects of the distribution of reaction strength and general characteristics in heavy-ion collision systems leading to the ^{214}Th composite system. Reaction products from the interaction of ^{48}Ti and ^{166}Er were studied recently using beams of 220, 240, 270, and 300 MeV from the ATLAS facility. Reaction products were registered over the angular range from 7.5° to 95° in an array of 9 single Si-detectors and two Si-detector telescopes. Fragment energy and mass distributions will be obtained from the measured pulse heights and flight time

over the 40 to 75 cm distance from the target to the detectors. A position-sensitive avalanche counter of $8 \times 10 \text{ cm}^2$ area was centered at 50° on the opposite side of the beam to facilitate the measurement of coincident reaction partners and allow for a test of two-body kinematics. The data obtained from this experiment are presently being analyzed.

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

The quasifission process is characterized by large or complete relaxation of the entrance-channel mass asymmetry without going through a step of compound nucleus formation. This process accounts for a substantial fraction of the reaction cross section in interactions between heavy targets and projectiles in the $A = 35\text{--}70$ mass region. The observed correlations between fragment mass and scattering angle allows for an estimation of the reaction time as shown in recent analysis of ^{238}U -induced reactions. Furthermore, the correlation between the mass drift and the reaction time indicates that the relaxation of the mass-asymmetry degree of freedom represents a damped motion with a characteristic time constant, which is independent of the temperature of the system. This points to the conclusion that the one-body dissipation mechanism is responsible for the energy damping in the mass-asymmetry mode.

Studies of the quasifission reaction have been carried out mainly with uranium projectiles using the kinematic coincidence technique. Because nuclei in the uranium region are highly fissile a substantial fraction of the products corresponding to large mass asymmetries were lost by sequential fission of the uranium-like reaction partner.

In order to avoid this problem, we have carried out an experiment to study the quasifission process for the $^{58}\text{Ni} + ^{208}\text{Pb}$ system at beam energies of $E = 320, 410, 500, 560 \text{ MeV}$. The choice of a ^{208}Pb target substantially reduces the ambiguities associated with sequential fission.

Cross sections, angular and energy distributions of single fragments from the reaction were measured using an array of 12 single-surface barrier detectors

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in the angular range $\theta = 10^\circ - 120^\circ$. The mass of reaction products will be determined from the time of flight of the products over the 40-60 cm distance from the target to the detectors using the time structure of the beam.

A position-sensitive Breskin-type detector with an active area of $8 \times 10 \text{ cm}^2$ was placed on the opposite side of the beam axis from the array of Si detectors. This will enable us to overdetermine the kinematics for two-body processes and obtain an estimate of the contribution from three-body reactions, which may not be negligible at the higher bombarding energies. Such reactions consist mainly of sequential fission of Pb-like nuclei, which are highly excited in a primary deeply-inelastic process. The data from this experiment are being analyzed.

- i. Angular Momentum in the Fission Process (W. R. Phillips, I. Ahmad, R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, J. Durell,* W. Gelletly,* and M. W. Drigert†)

Angular-momentum information in the fission process has been deduced from the measurement of multiplicity in the fission of the ^{216}Ra compound nucleus. This compound nucleus was produced by the $^{19}\text{F} + ^{197}\text{Au}$ reaction at ATLAS at a bombarding energy of 120 MeV. At this energy this fissioning system has an average spin of 12 $\hbar$. We have measured γ - γ and γ -x-ray coincidences using the Compton-suppressed Ge, LEPS, and the BGO hexagons of the Argonne-Notre Dame BGO γ -ray facility. We have analyzed the γ -ray spectra in 36 final fragments. From this analysis we have deduced the average spin in the final fragments and average γ -ray multiplicity as a function of mass asymmetry. The results show that the average primary fragment spin varies with the mass asymmetry. A paper has been prepared and accepted for publication. Further analysis is in progress, now focussing on the spectroscopy of the fragments.

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- j. Magnetic Spectrometer Small-angle Measurements of Fission-fragment Angular Distributions (J. Toke,* I. M. Govil,* J. R. Huizenga,* W. U. Schröder,* J. L. Wile,* and W. P. Zank,* and K. E. Rehm)

It is well known that the deviations of the angular distributions of the fission-like reaction fragments from the $1/\sin(\theta)$ pattern at small angles reflect excitation of the tilting mode in the nuclear complex involved. In heavier systems and/or at higher angular momenta, where the balance of acting forces is dominated by the disruptive ones, there is not enough time to achieve full relaxation in the tilting degree of freedom. In such systems then, the small-angle angular distributions provide the means for studying the relaxation process itself and hence should provide additional experimental input for developing theoretical models such as, e.g., one-body transport models. With this goal in mind, the angular distributions of the fission-like products from the $^{58}\text{Ni} + ^{165}\text{Ho}$ reaction were measured in an angular range of $3^\circ - 20^\circ$ and at two energies, $E_{\text{Lab}} = 406 \text{ MeV}$ and 580 MeV . The Enge split-pole magnetic spectrograph was employed to successfully divert the high elastic yield out of the detection system while still accepting, with high efficiency, the fission-like products. The detection system consisted of a position- and incidence-angle-sensitive $\Delta E - E$ focal-plane detector. The results available at the present stage of the data reduction are quite encouraging as far as the purity and the collected statistics are concerned. There is still a considerable effort required to achieve the complete and the best possible Z-calibration.

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- k. Asymmetric Fission in Light Nuclear Systems (S. J. Sanders, B. B. Back, C. Beck, B. K. Dichter, D. Henderson, R. V. F. Janssens, S. Kaufman, J. Keller, D. G. Kovar, C. F. Wang, B. Wilkins, F. Videbaek, C. F. Maguire,* and W. W. Prosser, Jr.†)

We are studying the fusion-fission process in light nuclear systems. This reaction mechanism has been largely ignored in light systems even though, as can now be shown, it has significant cross section at higher energies. The competition between fission and light-particle evaporation is sensitive to the shape of the potential energy surface of the compound nucleus and, as such,

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tests our understanding of nuclear structure under extreme conditions of energy and spin. We have measured cross sections for the two-body channels populated in the $^{32}\text{S} + ^{24}\text{Mg}$ reaction at $E_{\text{cm}} = 51.8$ and 60.8 MeV using a coincidence technique which allows correction for secondary light-particle evaporation.¹ The data show reaction yields with full equilibration of energy and mass-asymmetry coordinates. This work follows an earlier measurement where we were able to show that many aspects of similar fully-damped yields in the $^{16}\text{O} + ^{40}\text{Ca}$ reaction (reaching the same ^{56}Ni compound system) can be characterized in terms of a fusion-fission mechanism.² Figure I-9 shows our measured mass distributions for the $^{32}\text{S} + ^{24}\text{Mg}$ fully-energy-damped yields. The open histograms are the observed cross sections in the different mass channels. The shaded histograms indicate the primary, pre-evaporation mass distributions derived using the coincidence data. The primary mass distributions show an asymmetric behavior with little, if any, memory of the entrance channel. Our results should lead to a better understanding of the limitations to fusion in light systems, and may help to clarify the current speculation that certain heavy-ion resonance behavior result from fusion-fission through highly-deformed, compound-nucleus configurations. We have recently expanded our study of the $^{32}\text{S} + ^{24}\text{Mg}$ reaction in a particle- γ coincidence experiment using the γ -Ray Facility to determine the energy division between the reaction products and to further improve our resolution of the primary (pre-evaporation) mass distribution.

¹ S. J. Sanders, D. G. Kovar, B. B. Back, C. Beck, B. K. Dichter, D. Henderson, R. V. F. Janssens, J. G. Keller, S. Kaufman, T.-F. Wang, B. Wilkins, and F. Videbaek, Phys. Rev. Lett. 25, 2856 (1987).

² S. J. Sanders, R. R. Betts, I. Ahmad, K. T. Lesko, S. Saini, B. D. Wilkins, F. Videbaek, and B. K. Dichter, Phys. Rev. C 34, 1746 (1986).

Fig. I-9. Mass distributions for fission cross sections from the $^{32}\text{S} + ^{24}\text{Mg}$ reaction at $E_{\text{cm}} = 51.9$ and 60.8 MeV. The open histograms are the observed cross sections. The solid bars are the cross sections adjusted for secondary light-particle evaporation.

1. Study of the $^{28}\text{Si} + ^{28}\text{Si}$ Reaction using Heavy-ion γ Coincidences
 (B. K. Dichter, S. J. Sanders, R. R. Betts, M. W. Drigert,*
 R. Holzmann, R. V. F. Janssens, W. Kühn,† T. L. Khoo, W. C. Ma, and
 T. F. Wang)

We are studying heavy-ion γ coincidences from $^{28}\text{Si} + ^{28}\text{Si}$ reactions leading to binary reaction channels to help establish the origin of the heavy-ion resonances observed in $^{28}\text{Si} + ^{28}\text{Si}$ scattering experiments. These resonances have been suggested to result from the decay of superdeformed (3:1 axis ratio) shape isomers in ^{56}Ni and, as such, should result in the preferential population of prolate states in the symmetric and nearly-symmetric exit channels. Identification of these states should be achievable through measurement of their decay γ -rays. In an earlier experiment we tested the feasibility of doing the necessary heavy-ion γ coincidence measurement to test the shape-isomer hypothesis. In that measurement the heavy ions were detected in two ΔE -E silicon surface-barrier detector telescopes located at $\pm 45^\circ$. The coincident γ -rays were measured using 6 Compton-suppressed Ge detectors and 13 BGO detectors of the ANL-Notre Dame γ -Ray Facility. Gated on specific particle groups, the associated γ -ray spectra were found to be quite clean and the stronger transitions could be easily identified. In this initial measurement, however, we did not accumulate enough particle- γ coincidences to identify weaker transitions. Furthermore, the angle (and corresponding Q-value) resolution of the particle detectors was insufficient to fully Doppler correct the γ -ray spectra. We now plan a follow-up experiment with good angle resolution in the particle detectors and with sufficient statistics to resolve weaker transitions.

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

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

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

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

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

The recent observation of the fission decay of ^{56}Ni formed via the $^{32}\text{S} + ^{24}\text{Mg}$ entrance channel has, for the first time, shown the importance of this decay mode for light systems. In this case the mass distribution of fully-damped fragments was found to be asymmetric, as expected from calculations of fission from an equilibrated intermediate system.

In order to further establish this phenomenon in light systems we have measured fully-damped fragments from the $^{40}\text{Ca} + ^{40}\text{Ca}$ system at bombarding energies of 197 and 230 MeV. The experiment used six time-of-flight telescopes placed at angles between 10 and 50 degrees operated in singles and in coincidence with a large-area Breskin/Bragg detector mounted at -30 degrees. Analysis of these data has revealed a number of interesting features. The cross sections for the fully-damped fragments ($Q = Q_{\text{Viola}}$) show a $1/\sin\theta$ angular dependence as expected for decay of an equilibrated system with a lifetime long compared to the rotation time. The mass distribution of these fragments (Fig. I-10), instead of being featureless, shows a strong enhancement of every fourth mass; similar to that observed in the lighter systems such as $^{28}\text{Si} + ^{28}\text{Si}$ and $^{32}\text{S} + ^{24}\text{Mg}$. This structure is confirmed in the analysis of the coincidence data which, in addition, suggests that roughly two units of mass have been evaporated from the fragments prior to detection. Calculations of the decay of such excited fragments indeed predict some structure in the final-state yields due to evaporation, but somewhat different to that observed. We therefore, at this stage, believe that the structure is a new feature of heavy-ion interactions in this mass region and most probably reflects some structure in the potential energy surface arising from shell effects at large deformations.

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Fig. I-10. Mass distribution of damped reaction products from $^{40}\text{Ca} + ^{40}\text{Ca}$ at a bombarding energy of 200 MeV (solid line). The dashed curve shows the result of a calculation simulating statistical decay from excited fragments.

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

Measurements of the $^{16}\text{O} + ^{40}\text{Ca}$ reaction at $E_{\text{lab}}(^{16}\text{O}) = 13.4 \text{ MeV/u}$ were performed to determine the complete and incomplete fusion cross section. Five time-of-flight detectors (located in the angular range $2^\circ < \theta_{\text{lab}} < 52^\circ$) were used to identify the masses of the reaction products and extract velocity spectra. Two large-area low-pressure multi-wire proportional counters (located on the opposite side of the beam) were used in coincidence to identify the binary processes (quasielastic, deep-inelastic, and fission products). Twenty light-charged-particle detectors (located $4^\circ < \theta_{\text{lab}} < 165^\circ$ and $-4^\circ > \theta_{\text{lab}} > -165^\circ$) were operated in coincidence to establish the light-particle angular correlations. Analysis of the singles data has been completed and is in the process of being submitted for publication. The total cross sections for evaporation residues from complete fusion ($\sigma_{\text{ER}}^{\text{CF}} < 475 \text{ mb}$) and incomplete fusion ($\sigma_{\text{ER}}^{\text{ICF}} > 300 \text{ mb}$) were extracted utilizing velocity spectra predicted by evaporation codes. Model simulations of two sources and multi-sources indicate that the details of the velocity distributions of the evaporation residues as a function of mass and detected angle are sensitive to the character of the pre-equilibrium light particles emitted, which potentially can be utilized more quantitatively in the identification of incomplete fusion yields in the coincidence results. The cross section for yields consistent with fission was extracted and together with the evaporation residue cross section allowed extraction of a value for the total complete fusion cross section. Analysis of the coincidence results was postponed until the singles data had been analyzed (i.e., until data reduction and model calculations had been performed), but are well underway at this time.

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¹C. 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 (to be submitted to Phys. Rev. C).

Preliminary analysis indicates that the coincidences with the large-area gas detectors will allow a more quantitative determination of the fission cross sections, and identification of fission products associated with pre-equilibrium emission of light particles. The coincidences with the light-charged particles will allow verification of conclusions drawn from the model calculations performed for the singles results.

- p. Energy Dependence of Complete and Incomplete Fusion in $^{28}\text{Si} + ^{28}\text{Si}$
(M. Vineyard,* D. G. Kovar, C. Beck, D. J. Henderson, R. V. F. Janssens, B. D. Wilkins, C. F. Maguire,† F. W. Prosser,‡ and G. S. F. Stephens§)

Time-of-flight measurements were performed last year for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at bombarding energies of 11, 14.3, and 16 MeV/u to establish the total evaporation-residue cross-section behavior for complete and incomplete fusion. The measurements were motivated by the observation of a significantly different behavior of the evaporation-residue cross section for the $^{16}\text{O} + ^{40}\text{Ca}$ and $^{28}\text{Si} + ^{28}\text{Si}$ reactions (forming ^{56}Ni) at laboratory bombarding energies greater than 8 MeV/u.¹ Another feature of the reaction, which was not understood, was the evidence for incomplete fusion contributions in the case of $^{16}\text{O} + ^{40}\text{Ca}$, which appears to be absent in the $^{28}\text{Si} + ^{28}\text{Si}$ case. The absence of incomplete fusion yields for the symmetric entrance channel $^{28}\text{Si} + ^{28}\text{Si}$, if true, would suggest an entrance-channel dependence for the incomplete fusion process. Such a picture is consistent with Fermi sphere models² in which the relative velocities of the interacting nuclei with respect to the center of mass are the relevant parameters for determining whether incomplete fusion processes occur. The present measurements were hence performed at bombarding energies where, in the framework of the Fermi sphere models, incomplete fusion processes should begin to contribute. The results of these measurements have been reduced and analyzed.³ The observed

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¹D. G. Kovar, Proceedings of the 5th Adriatic Int. Conf. on Nuclear Physics, Croatia, Yugoslavia, Sept. 1984 (World Scientific, 1984), ed. N. Cindro, W. Greiner, and R. Caplar, pp. 185-204.

²e.g., G. S. F. Stephens et al., Phys. Lett. 161, 60 (1985).

³M. F. Vineyard et al., Bull. Am. Phys. Soc. 33, 928 (1988).

evaporation residue velocity distributions were found to be broader than predicted by evaporation calculations. The component of the evaporation residue yields consistent with complete fusion was extracted using the predicted velocity distributions, resulting in upper limits for the complete fusion evaporation-residue cross sections. At bombarding energies of 11 and 13.4 MeV/u, the extracted cross sections are found to contribute 73% and 59%, respectively, to the total evaporation-residue cross section. These results are in agreement with the simple Fermi sphere model.² Further work using two-source model simulations to decompose the evaporation residue yields is underway for the higher bombarding energy.

- q. Energy Dependence of Complete and Incomplete Fusion in the $^{28}\text{Si} + ^{12}\text{C}$ Reaction (J. Mateja, D. G. Kovar, M. Vineyard, C. Beck, D. J. Henderson, R. V. F. Janssens, B. D. Wilkins, C. F. Maguire,* F. W. Prosser,† and G. S. F. Stephens§)

Time-of-flight measurements were performed for the $^{28}\text{Si} + ^{12}\text{C}$ reaction at laboratory bombarding energies of 11.0, 14.3, and 16.0 MeV/u to establish the total evaporation residue cross section for complete and incomplete fusion. The measurements were motivated by observations suggesting that incomplete fusion processes were dependent on the entrance-channel mass asymmetry. To study possible entrance-channel effects, measurements for the system $^{28}\text{Si} + ^{12}\text{C}$, $^{28}\text{Si} + ^{28}\text{Si}$, and $^{28}\text{Si} + ^{40}\text{Ca}$ were performed. The velocity spectra of the mass-resolved evaporation residues were compared with velocity spectra predicted by evaporation-model calculations to identify the yields consistent with complete fusion. The analysis of the $^{28}\text{Si} + ^{12}\text{C}$ system revealed that (1) the cross sections extracted for complete fusion are significantly larger than implied by previous results reported in the literature,¹ (2) the ratio of complete fusion to the total evaporation-residue cross section as a function of bombarding energy is consistent with systematics,² which indicates an entrance-channel dependence of incomplete fusion processes, and (3) the

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¹B. A. Harmon et al., Phys. Rev. C 34, 552 (1986)

²H. Morgenstern et al., Phys. Rev. Lett. 52, 1104 (1984).

evaporation residue velocity distributions as a function of mass and angle are sensitive to the character and details of the pre-equilibrium emission. This last result can potentially be used to distinguish more quantitatively than previously possible the yields arising from the complete and incomplete fusion reactions.

- r. Incomplete Fusion in Heavy Asymmetric Systems: $^{12}\text{C} + ^{197}\text{Au}$
(I. Tserruya,* V. Steiner,* Z. Fraenkel,* D. G. Kovar, C. Beck,
D. J. Henderson, B. G. Glagola, B. D. Wilkins, C. F. Maguire,†
and F. W. Prosser‡)

Coincidence measurements between evaporation residues and light charged particles were performed for the $^{12}\text{C} + ^{197}\text{Au}$ reaction at $E_{\text{lab}}(^{12}\text{C}) = 120$ MeV. The experiment was motivated by the results of previous singles measurements of ^{12}C -induced reactions on targets of ^{90}Zr , ^{120}Sn , ^{160}Gd , and ^{197}Au over an energy $4 < E_{\text{lab}} < 11$ MeV/u.¹ In these measurements the velocity spectra of the evaporation residues showed evidence of incomplete fusion processes beginning to contribute at low bombarding energies near the Coulomb barrier and growing rapidly with bombarding energy. This behavior implied that the mechanism responsible is something like a "massive transfer" process, but coincidence measurements establishing the angular distributions and energy spectra of the pre-equilibrium light particles associated with the incomplete fusion products were necessary to draw a firm conclusion. In the coincidence experiment, the evaporation residues were detected in a large-area low-pressure multi-wire proportional counter situated at either zero degrees (immediately behind a small beam stopper) or at 15 degrees, allowing a coverage of angle $1.5 < \theta_{\text{lab}} < 24$ degrees. Fifteen detectors (five out-of-plane) were located in the angular range $5 < \theta_{\text{lab}} < 165$ degrees and were used to detect the light particles in coincidence with the evaporation residues. The on-line analysis showed that primarily alpha particles were in coincidence with the incomplete fusion yields. The results are presently under analysis.

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¹I. Tserruya et al., Phys. Rev. Lett. 60, 14 (1988).

s. Incomplete Fusion in Heavy Asymmetric Systems: $^{14}\text{N} + \text{A}(100-200)$
 (D. G. Kovar, Z. Fraenkel,* V. Steiner,* and I. Tserruya*)

Measurements of the time-of-flight spectra of evaporation residues produced in $^{14}\text{N} + ^{120}\text{Sn}$, ^{159}Tb , and ^{197}Au reactions at $E_{\text{lab}}(14) = 74.2$ MeV were performed at the Weizmann Institute to study the projectile dependence of incomplete fusion at lower bombarding energies. Based on the results of ^{12}C -induced reactions performed previously at the Weizmann Institute and ATLAS, incomplete fusion processes are present at low bombarding energies (starting near the Coulomb barrier), and grow rapidly in strength with increasing bombarding energy.¹ This behavior suggests that something like a "massive transfer" reaction is responsible for incomplete fusion at the lower bombarding energies, and that the $(^{12}\text{C}, \alpha)$ reaction, in particular, is primarily responsible for the incomplete fusion yields observed. Coincidence measurements were performed this year for the $^{12}\text{C} + ^{197}\text{Au}$ reaction to further substantiate this interpretation. In such a massive transfer, the binding energies and nuclear structures of the nuclei should have an important influence on the magnitude of the cross section. Reactions induced by ^{14}N were chosen for study in the expectation that the unfavorable Q-values and spectroscopic factors for the $(^{14}\text{N}, \alpha)$ reactions would result in reduced incomplete fusion cross sections. Difficulties in obtaining ^{14}N beams prevented the measurements over the energy range planned ($3 < E_{\text{lab}} < 8$ MeV/u), and results at only a single bombarding energy ($E_{\text{lab}} = 74.3$ MeV) were collected. Only for the $^{14}\text{N} + ^{120}\text{Sn}$ reaction could evidence for incomplete fusion yields be seen, with a cross section that is a factor of 2-3 times smaller than that observed in the ^{12}C -induced reaction at a comparable energy above the Coulomb barrier. While indicative of a projectile dependence, more complete measurements over a range of bombarding energies are needed. An experiment to study the evaporation residues produced in the $^{14}\text{N} + ^{159}\text{Tb}$ reaction in coincidence with gamma-rays and light-charged particles will pursue this question of the mechanism of incomplete fusion at low bombarding energy.

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¹I. Tserruya et al., Phys. Rev. Lett. 60, 14 (1988).

- t. Pre-equilibrium Light-particle - Light-particle Coincidence Measurements at $E > 10 \text{ MeV}/\mu$ (P. A. DeYoung,* C. J. Gelderloos,* K. Zienert,* R. L. McGrath,† J. M. Alexander,† G. Gilfoyle,† M. S. Gordon,† D. G. Kovar, C. Beck, and M. Vineyard)

Light particles (p,d,t, α) from the reaction of ^{16}O with ^{27}Al have been measured at several beam energies (215 MeV and 250 MeV at ANL and 80 MeV and 140 MeV at SUNY). The analysis of the 215- and 140-MeV runs is well along and is yielding interesting results.¹ For both energies, the light-particle singles cross sections have been extracted and converted into the Lorentz invariant cross section. At back angles, the emission pattern indicates isotropic emission from a source moving with the velocity of the compound nucleus, while at forward angles there is a clear fast component. Small-angle correlations were measured at an angle where the emission is dominated by compound nucleus evaporation. From these coincidence data, the p-p, p- α , d- α , and α - α correlation functions have been calculated. At 215 MeV the correlation functions show the expected positive peaks due to unbound resonances in the various two-particle systems and a suppression at low relative momenta due to Coulomb repulsion. The magnitude of the peaks and suppression is larger than observed at 140 MeV and smaller than found by the MSU group at 400 MeV.² The functions can be fit by quantum-mechanical interference calculations³ (from D. Boal) if a space-time extent of 8 fm is assumed. This is much smaller than expected for a compound nucleus at this energy. Several explanations for this behavior are being pursued. Future plans call for detailed comparison of the 215-MeV results to several models (quantum, classical trajectory, resonant particle emission) to complete that phase of the investigation. The analysis of the other two energies is continuing.

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†SUNY Stony Brook, Stony Brook, L.I., New York.

¹P. A. DeYoung et al., Bull. Am. Phys. Soc. 33, 928 (1988)

²D. Boal et al., Phys. Rev. C 33, 549 (1986).

³M. A. Bernstein et al., Phys. Rev. Lett. 54, 402 (1985)

- u. Measurements of Fragment Emission from the $^{16}\text{O} + ^{27}\text{Al}$ System
 (G. Gilfoyle,† J. M. Alexander,† G. Auger,† S. Cox,† M. Gordon,†
 R. L. McGrath,† P. A. DeYoung,* C. J. Gelderloos,* D. Kortering,*
 K. Zienert,* D. Kovar, C. Beck, and M. Vineyard)

We have measured fragments with $A > 4$ emitted from the $^{16}\text{O} + ^{27}\text{Al}$ system at the beam energies of 215 MeV and 250 MeV. Both singles and coincidences were recorded at fragment angles extending from 7 to 45 degrees. At the lower energy several unusual results were found.¹ The angular distributions for all masses were much broader than predicted by the statistical model for complete or incomplete fusion. The centroids of the velocity spectra are shifted to smaller values than expected indicating incomplete momentum transfer and the mass distributions are also not reproduced by calculation and show considerable cross section for masses as low as $A = 19$. Simulations are in progress to understand these results. The higher-energy experiment, currently under analysis, had many more fragment detectors than the earlier experiment and is also expected to give insight into the mechanisms responsible for these phenomena.

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¹G. Gilfoyle et al., Bull. Am. Phys. Soc. 33, 978 (1988).

C. HIGH ANGULAR MOMENTUM STATES IN NUCLEI

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

All of these projects have benefitted greatly from the Argonne/Notre Dame BGO γ -ray facility. For most of the year Phase I of this construction project (8 Compton-suppressed Ge (CSG) detectors and a multiplicity filter of 14 hexagonal BGO detectors) was used very heavily, but the complete system (Phase II with a sum-energy/multiplicity inner array of 50 elements surrounded by 12 CSG's) became fully operational in early December. Further developments on this facility are still planned: a scattering chamber for coincidence measurements between γ -rays and particles identified by time of flight is under construction, a mechanical support has been constructed to place several CSG's around a small scattering chamber at the spectrograph and initial design studies are taking place to use the entire facility or parts of it in conjunction with the Fragment Mass Analyzer.

Research on octupole shapes continued to focus mainly on the very neutron-rich nuclei around ^{146}Ba . Last year, we reported evidence for octupole deformation in $^{144,146}\text{Ba}$. These nuclei have a very large neutron excess and cannot be studied with the usual in-beam techniques. Level schemes have, however, been obtained from a study of γ - γ coincidences from ^{252}Cf fission fragments. These studies have now been extended to the $^{146,148,150}\text{Ce}$ isotopes. As in the case of $^{144,146}\text{Ba}$, interlaced positive- and negative-parity levels connected by fast electric dipole transitions have been observed in ^{146}Ce but not in $^{148,150}\text{Ce}$. These data indicate that octupole shapes occur in a limited number of nuclei in this region, in agreement with recent theoretical descriptions. Studies of reflection asymmetric shapes in actinide nuclei have focussed on ^{219}Ac and ^{223}Ac . Complex band structures have been established in ^{219}Ac which is located at the border of the predicted region of octupole deformation. It is hoped that these data will lead to a better understanding of the single-particle structure in this region. Evidence for octupole deformation near the ground state was established in ^{223}Ac .

Research on nuclear structure at very high spin concentrated mainly on the nuclei ^{154}Dy and $^{147,148}\text{Gd}$. In ^{154}Dy our efforts have focussed mainly on the extension of the yrast band towards higher spins and on the study of the state lifetimes. Marked structural changes occur as a function of spin along the yrast line with a transition from prolate to oblate shape, followed by an unexpected return to moderate collectivity at the highest spins. Structural changes with increasing energy above the yrast line are also observed. In ^{148}Gd evidence was found for superdeformation from γ - γ transition energy correlation measurements. The deduced moment of inertia $I^{(2)} = 78 \mu^2 \text{ MeV}^{-1}$ is consistent with superdeformation. The results can be explained by cranked Strutinsky calculations. A similar search for superdeformation in ^{147}Gd was negative.

Information on the properties of the compound nucleus decay came from two types of investigation. The gamma decay of a compound nucleus after particle evaporation was studied by measuring the total γ -ray spectrum with the CSG's. The emphasis this year was placed on a comparison between the quasicontinuous part of the spectra from $^{152,154,156}\text{Dy}$ when these three nuclei are produced with very similar angular momentum and excitation energy. In ^{152}Dy , where the yrast states are of single-particle character, a region up to

1-2 MeV above the yrast line also has similar character. At higher energy and spin, these single-particle states give way to collective E2 structures. In ^{156}Dy , where the yrast states are characteristic of a prolate rotor, the structure above the yrast line is of similar character; i.e. the collective E2 bump sets in immediately. As indicated above, the ^{154}Dy nucleus exhibits shape changes along the yrast line. Its quasicontinuum spectrum consists of a low-energy dipole part and a strong E2 bump with two distinct components at ~ 800 and 1250 keV. Both components correspond to collective fast decays and it was established that the high-energy component occurs earlier in the γ -cascade and has properties similar to the E2 structures seen in $^{152,156}\text{Dy}$. The exact nature of the second component is not entirely clear at the moment, but the data suggest that it originates from the decay of quasivibrational states, possibly triaxial in nature, which occur at excitation energies below 17 MeV. Our investigations of the stage preceding γ -ray emission have focussed on the origin of the suppression of neutron emission seen in some heavy-ion-induced fusion reactions. It appears that the initial stage of the decay could be influenced by shell-structure effects.

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

- a. Charged-particle Gamma-ray Coincidences as a Probe of Nuclear Structure at High Spin (R. R. Betts, B. Dichter, M. Drigert,* R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, S. J. Sanders, and W. Kühn†)

The energy spectra and correlations of particles emitted by hot nuclei potentially contain significant information on the properties of the emitting system. The spectra of charged particles are of particular interest in that they are, in principle, sensitive to the shape of the emitting system through the dependence of the emission barrier for charged particles on the orientation of the nucleus relative to the direction of emission. A number of experiments have been reported in the literature in which such effects have been claimed. In most cases, however, the detailed origin of the emitted particles is open to question, sources other than emission from the compound nucleus not being excluded. With this in mind we have started a series of experiments in which protons and alpha particles are detected in coincidence with discrete gamma rays, thereby unambiguously identifying the final nuclei populated in the decay chain.

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The initial experiment was carried out using a small scattering chamber placed at the center of the Argonne-Notre Dame BGO gamma-ray facility. Protons and alpha particles evaporated following the fusion of $^{64}\text{Ni} + ^{92}\text{Zr}$ at a bombarding energy of 239 MeV were detected in two counter telescopes placed at 0 and 75 degrees, respectively. Spectra were obtained by gating on discrete lines in ^{151}Dy , ^{152}Dy and ^{153}Ho , thereby identifying alpha particles and protons from the (α, n) $(\alpha, 2n)$ and $(p, 2n)$ decay channels of the compound nucleus ^{156}Er . The essential result contained in these data is the large anisotropies observed for the lowest-energy particles emitted which, in the geometry used, also implies a favoring of emission perpendicular to the compound nucleus spin direction. This anisotropy is far in excess of that expected for emission from a spherical source and is in the direction expected for emission from a deformed source. Quantitative calculations of this effect are, however, unable to account for the magnitude of the observed effect and we must wait before definitive statements on the shape of the emitting system can be made.

These experiments will be continued using an improved setup in the new scattering chamber constructed for the gamma-ray facility. A wide range of systems will be investigated using both near-symmetric and asymmetric entrance channels including nuclei whose shapes at high excitation have previously been investigated using high-spin giant-dipole gamma rays.

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

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

This picture has so far been checked mainly by comparing experimental and calculated energies of yrast levels in transitional nuclei. It is important to extend these comparisons to non-yrast levels as well.

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The crucial tests rest in lifetime measurements, since these provide a direct measure of collectivity. Finally, by tracing the yrast line to higher spins one can ascertain if the oblate coupling scheme persists beyond the maximum spin which can be generated by the valence nucleons.

With these motivations in mind, we performed a series of experiments at ATLAS using the BGO gamma-ray facility. The $^{122}\text{Sn}(^{36}\text{S}, 4n)^{154}\text{Dy}$ reaction at 165 MeV was used. A total of 135 million true prompt-coincidence events were obtained from a stacked target which allowed the residues to recoil into vacuum in order to avoid Doppler broadening for fast gamma rays, and 55 million from a lead-backed target in which the residues stopped in ~ 2 ps. By examining the slowing-down process of the residues in the stopping material of the backed target, lifetimes of fast gamma-rays could be extracted using the Doppler-shift attenuation method. Finally, lifetimes of longer-lived states were measured with the recoil-distance method (RDM) using a plunger device.

More than 50 new transitions have been placed in the level scheme of ^{154}Dy . An impressive series of nuclear structure changes along the yrast line have been observed (Fig. I-11): the ground-state band (gsb) is crossed at 16^+ by an aligned $\nu i_{13/2}$ S-band, which then continues as the yrast structure to 32^+ , while the gsb continues as an excited band to 26^+ . Both bands are crossed at these spins by structures whose irregular energies and lifetimes suggest the approach toward aligned-particle configurations. However, for spin $38^+ - 48^+$, the yrast structure exhibits moderate collectivity ($Q_0 = 198 - 243$ e.b.; $B(E2) = 29 - 43$ W.u.). The observation of several non-yrast levels has also made it possible to see a change of structure with increasing excitation energy above the yrast line, and to follow the descent of oblate aligned-particle configurations towards the yrast line with increasing spin until they cross both the gsb and $\nu i_{13/2}$ band. The theoretical predictions in the band-terminating picture impressively account for the observed features for $I < 36$. The return of collectivity at higher spins was, however, not predicted, thereby raising challenging questions about the nature of collectivity at the highest spins.

A paper has been written and submitted for publication. Further data analysis will concentrate first on the lifetimes of negative parity levels in ^{154}Dy , and then on the level scheme and lifetimes of ^{153}Dy .

Fig. I-11. Level energy (after subtraction of a rotational term) vs. spin for positive parity levels; connecting transitions are shown, thereby exhibiting the structural connections of states. Transitions within the ground band, the S-band, and the moderately collective band at the highest spins are shown as open, heavy and medium arrows, respectively; demonstrated or probable single-particle transitions are shown as thin lines. The numbers by the highest spin transitions are $B(E2)$ values in W.u.

- c. Experimental Evidence for Superdeformation in ^{148}Gd
 (R. V. F. Janssens, R. Holzmann, R. R. Chasman, I. Ahmad, T. L. Khoo,
 W. C. Ma, B. K. Dichter, H. Emling, M. W. Drigert,* J. Borggreen,†
 P. J. Daly,‡ U. Garg,* Z. W. Grabowski,‡ M. Piiparinen,‡ M. Quader,‡
 D. C. Radford,§ and W. Trzaska#)

The recent discovery of a sequence of discrete transitions in ^{152}Dy corresponding to the rotation of a nucleus with a superdeformed shape has generated great interest, from both the experimental and theoretical points of view. Many questions remain unanswered, such as the exact excitation energy of the superdeformed band, its feeding mechanism in (H.I.,xn) fusion reactions and the magnitude of the pairing effects in the bands. Among these questions those related to the mapping of the regions of the nuclear chart where superdeformed shapes occur require immediate attention. Here we report on evidence for superdeformation in ^{148}Gd based on transition-energy correlations. This study is an extension of earlier work on the discrete spectroscopy of ^{148}Gd into the quasicontinuum.

^{148}Gd was produced using a 170-MeV ^{36}S beam from the ATLAS accelerator bombarding a 0.8-mg/cm² ^{116}Cd target evaporated on a 10-mg/cm² Pb foil. The data were obtained with the BGO gamma-ray facility which consisted at the time of 7 Compton-suppressed Ge spectrometers surrounding a central array of 14 BGO hexagons providing multiplicity and time information.

In the analysis several energy-correlation matrices were constructed for all coincidences between all pairs of detectors. Only the matrix where prompt events were collected, assuming that all gamma-ray lifetimes are fast with respect to the slowing-down time in the Pb foil, showed structures of interest in the present discussion. In this case the gamma rays were corrected for Doppler shifts assuming full recoil velocity.

A ridge-valley structure was found in the matrix (Fig. I-12). This correlated structure was identified between 1.00 and 1.42 MeV. The average width of the valley was found to be 102 $\pm$ 8/-4 keV which corresponds to a value of 78 $\pm$ 3/-6 MeV^{-1} for the dynamic moment of inertia. This value is 1.36 times the rigid-body moment of inertia for a spherical nucleus of mass 148 and is only

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Fig. I-12. Cuts perpendicular to the diagonal of the symmetrized, Doppler shift corrected, E_{γ_2} - E_{γ_2} matrix for the energy intervals indicated. Only 20-keV wide energy slices which are not contaminated with contributions due to discrete lines have been added up. The arrows indicate the observed position of the first ridge and the expected positions of the second and third ridges.

slightly smaller than the one observed in ^{152}Dy . We thus conclude that ^{148}Gd develops a very large deformation. The half width of the ridge was found to be rather constant: 9.2 ± 3.2 keV. This suggests that the correlated structure is made up of several gamma-ray cascades with different moments of inertia. This conclusion is consistent with the fact that extensive efforts to identify transitions forming a discrete superdeformed band were unfruitful. The present data are explained rather well by Strutinsky calculations by R. R. Chasman described elsewhere in this report. A paper reporting these results has been accepted for publication.

Efforts to study superdeformation further are continuing and are described elsewhere in this report.

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

As part of our efforts to identify the nuclei at the beginning of the rare-earth region where superdeformation occurs, we have studied the nucleus ^{151}Dy . This experiment was performed with the recently completed BGO gamma-ray facility. Hence, an array of 50 BGO detectors was covering most of the area around the target. Twelve Compton-suppressed Ge detectors were located outside the array in 2 rings.

The reaction $^{122}\text{Sn}(^{34}\text{S}, 5n)$ was used at a beam energy of 174 MeV. The target consisted of 3 thin self-supporting $300\text{-}\mu\text{g}/\text{cm}^2$ foils. The recoiling nuclei were stopped 10 cm from the target in a Pb foil. Events where at least 2 Ge detectors and 5 elements of the inner array fired were recorded on tape together with the multiplicity and total sum-energy information.

Identification of the final nuclei by isomer tagging was also possible and the relevant time and multiplicity information was also collected. A total of 330 million coincidence events was accumulated.

It should be pointed out that the beam energy was chosen such that the excitation energy and angular-momentum inputs in the ^{151}Dy nucleus are similar

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to the ones at which discrete superdeformed bands have been seen in ^{152}Dy at Daresbury and in ^{149}Gd at Chalk River.

A rotational band of 19 (possibly 20) transitions (see Fig. I-13) extending to spin $\sim 131/2 \hbar$ has been observed in ^{151}Dy with an average dynamic moment of inertia $\mathcal{F}^{(2)} = 79 \hbar \text{ MeV}^{-1}$. This band is identified as a superdeformed band in ^{151}Dy . The value of $\mathcal{J}^{(2)}$ agrees with cranked Strutinsky calculations. Similarities as well as striking differences with the superdeformed bands of neighboring nuclei are observed.

- e. Lifetimes of Very High-spin States in ^{156}Dy Through DSAM
 (H. Emling, I. Ahmad, B. Dichter, R. Holzmann, R. V. F. Janssens,
 T. L. Khoo, M. Drigert,* U. Garg,* P. J. Daly,† Z. Grabowski,†
 M. Piiparinen,† M. Quader,† and W. Trzaska†)

Compton-suppressed Ge detectors yield γ spectra with not only high resolution but very low background, particularly when only a single channel is selected, for example by coincidence with specific γ rays. The quality is such that the line shapes of individual lines reflect not only the lifetime of the decaying state but also the feeding history. A first attempt to exploit these features to measure lifetimes and feeding times of high-spin states in ^{156}Dy has been performed with the BGO γ -ray facility, where 6×10^7 coincidences were recorded with the $^{124}\text{Sn}(^{36}\text{S}, 4n)$ reaction. ^{156}Dy with $N = 90$ is the lightest Dy isotope where deformation becomes well established. Thus it is of interest to establish if the deformation is altered by rapid rotation, for instance if triaxial and oblate shapes set in. In addition, we would like to study the evolution of the quasicontinuum states with spin-internal excitation energy (above the yrast line) and neutron number by examining the total γ spectra of different Dy isotopes.

The results of this experiment can be summarized as follows:

- (i) lifetimes have been obtained for all yrast states in ^{156}Dy with spins between $I = 28^+$ and $I = 40^+$.
- (ii) for states with spin $I < 30 \hbar$ good agreement is found with the results of an earlier GSI experiment using the recoil-distance method.
- (iii) the value of the $B(E2)$'s for states with spin $28^+ < I < 40^+$ remains essentially constant.

Fig. I-13. Gamma-ray spectrum in ^{151}Dy obtained by summing coincidence gates on the selected transitions (577, 682, 734, 940, and 1194 keV) in the superdeformed band. Note that the higher part of the spectrum was compressed by a factor of 2. The Doppler correction is different for the upper part of the spectrum because of the shorter emission times of the high-energy transitions. The transition energies and the proposed spin assignments are included. The placement of the lowest transition is tentative.

These results suggest that there is no significant change in deformation between $I \approx 28^+$ and $I \approx 40^+$ even though changes in the structure of the nucleus are inferred from the level energies. The results of this work are being prepared for publication.

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- f. Structural Changes Above the Yrast Line in $^{152-156}\text{Dy}$ (R. Holzmann, T. L. Khoo, I. Ahmad, B. K. Dichter, H. Emling, R. V. F. Janssens, W. C. Ma, M. W. Drigert,* U. Garg,* D. C. Radford,† P. J. Daly,‡ M. Quader,‡ and W. Trzaska‡)

Dramatic structural changes have been observed near the yrast line in the isotopes $^{152-156}\text{Dy}$, which lie in the transitional region between spherical and deformed nuclei. Equally interesting changes are expected to occur with increasing internal excitation energy above the yrast line in these nuclei. To probe nuclear structure above the yrast line we have measured the quasicontinuum γ -ray spectra which are emitted from the highly-excited states. Compton-suppressed Ge detectors were used which allowed for reliable unfolding to obtain the actual spectra emitted by the nucleus. From the angular distribution and spectral shapes it has been possible to decompose the different components of the quasicontinuum spectra.

Prominent E2 components have been observed in all the nuclei studied; in each case the spectral shape was different (Fig. I-14). The most striking feature was in ^{154}Dy where, instead of the customary single, broad Gaussian-like peak, two such peaks were observed. One can immediately interpret these features as arising from structural changes occurring along the γ -deexcitation cascade. Without such changes only a single broad peak would have been observed. These results demonstrate that nuclear structure information can be directly observed in the quasicontinuum spectra.

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Fig. I-14. Measured ($\bullet$) E2 γ -quascontinuum components in $^{152},^{154},^{156}\text{Dy}$. Discrete lines have been subtracted and the spectra corrected for Doppler shifts and angular-distribution effects. Calculated spectra are shown as histograms.

Monte Carlo calculations which incorporate a competition between E2 and statistical decay were performed to gain insight into the excited states. These calculations allow assumptions about the nature of the states to be tested directly by comparison with the data. In each case, the experimental spectral shapes could be reproduced. The Doppler-shifts which arose from the recoil velocity of the residue as it slowed in its Pb backing were also reproduced, thus providing a measure of the collectivity associated with the E2 structures. In each case the cascade started with collective rotational structures with $Q_t \sim 7$ eb and $\mathcal{J} = 76 \hbar^2 \text{ MeV}^{-1}$. In ^{152}Dy this collective deexcitation towards the yrast line terminates, on the average, ~ 1.5 MeV above the yrast line around spin 29. At that point a structural change occurs and the cascade proceeds through oblate aligned-particle configurations which are present at and immediately above the yrast line. In ^{156}Dy the collective cascade continues to lower spins, eventually feeding into the yrast line which is collective in this nucleus. In ^{154}Dy , the initial rotational cascade gives way at $E^* \sim 17$ MeV to a vibrational-like cascade, where the transition energy remains constant (but with a spread) instead of decreasing with spin. The collectivity remains high (300 W.u.) during this part of the cascade.

Another unexpected observation in ^{154}Dy is the variation in spectral shape associated with feeding into different spin intervals or different bands near the yrast line. The impressive series of shape changes which occur near and along the yrast line in ^{154}Dy (see C.b) are accompanied by equally dramatic changes above the yrast line. The nature of the different structures which are encountered in the decay towards the yrast line in ^{154}Dy are fascinating but are still not understood and stand out as a challenge for theory to explain.

- g. Octupole Deformation in ^{146}Ce (W. R. Phillips,* R. V. F. Janssens, I. Ahmad, H. Emling, R. Holzmann, T. L. Khoo, and M. W. Drigert†)

Last year we performed $\gamma\gamma$ coincidence experiments with a ^{252}Cf source using 7 Compton-suppressed germanium spectrometers of the Argonne-Notre Dame γ -ray facility. A LEPS (low-energy photon spectrometer) was also used with the setup to measure the K X-rays and low-energy γ -rays. The aim of the experiment was to study level structures of neutron-rich fission fragments which are inaccessible by other means. From these studies we deduced octupole deformation in ^{144}Ba and ^{146}Ba . We have now analyzed the data on cerium isotopes and deduced the level structure of ^{146}Ce , ^{148}Ce , and ^{150}Ce . The results indicate that ^{146}Ce develops octupole deformation at spins above 6. At these high spins the positive- and negative-parity levels constitute a single rotational band, characteristic of reflection asymmetric shape. These effects are not observed in the other Ce isotopes (see Fig. I-15). We have deduced E1 transition rates in ^{146}Ce which are quite similar to the values measured in ^{144}Ba . These fast E1 transitions provide another evidence for octupole shape and are reproduced by a recent mean-field calculation of Nazarewicz. The present data further demonstrate the significance of neutron number 88 for octupole deformation.

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

The nucleus ^{219}Ac is located at the border of the region where stable octupole deformation has been reported. Early studies of this nucleus have indicated a rich band structure. In particular, alternating positive- and negative-parity bands connected by strong enhanced E1 transitions were seen. We used the power of the BGO gamma-ray facility to get more information on this nucleus. The reaction $^{209}\text{Bi}(^{13}\text{C}, 3n)$ at 73 MeV was used. The facility consisted of 14 hexagonal detectors of the inner array and 8 Compton-suppressed Ge detectors

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Fig. I-15. Partial decay schemes for $^{146,148}\text{Ce}$ and ^{150}Ce . The errors on the level energies and γ -ray energies are <0.2 keV; there is an additional uncertainty of 0.2 keV on the absolute γ -ray energies. The errors on the relative intensities vary from $\sim 30\%$ for the weak γ -rays to $\sim 5\%$ for the most intense. The spins and parities of the new levels established in this experiment are assigned by analogy with neighboring nuclei.

positioned at 90 and 145.5 degrees with respect to the beam. Two low-energy photon spectrometers for X-ray and low-energy gamma-ray detection were located at forward angles. A total of 126 million coincidence events were collected.

In a second experiment conversion electrons from the same nucleus were measured with the superconducting electron spectrometer. Here the electrons were measured using the spectrometer in a sweeping mode together with a special baffle for delta electrons. In this mode we were able to detect electrons with energies as low as 120 keV. Singles spectra as well as spectra in coincidence with low-energy gamma rays were recorded.

The analysis of the data is still in progress. At this stage it is, however, clear that our knowledge of the level structure will be greatly enhanced. The previously observed bands have been extended towards higher spins and other levels have been observed.

- i. A Fast El Transition in ^{223}Ac (I. Ahmad, R. Holzmann, R. V. F. Janssens, M. Huyse,* P. Dendooven,* and G. A. Leandert†)

According to recent theoretical calculations ^{223}Ac should have the maximum octupole deformation in the ground state of any nucleus. To check this prediction and to obtain a better understanding of interactions generating octupole shapes, we have carried out a spectroscopic study of ^{223}Ac . For this purpose we utilized the newly developed technique of ion guide at Louvain-la-Neuve, Belgium to produce mass-separated sources of ^{227}Pa (38 min). The ^{227}Pa sources were produced by the bombardment of a 6-mg/cm² ^{232}Th target with 55-MeV protons and were mass separated. Alpha singles and α - γ coincidence measurements were performed. These measurements confirmed the previous tentative spin-parity assignments. The splitting energy for the $5/2_{\pm}$ parity doublet is 64.8 keV, slightly larger than the value in the octupole deformed nucleus ^{225}Ac . We have also obtained an upper limit of 250 ps on the half-life of the 64.8-keV state which corresponds to a $B(\text{El})$ value of 0.003 W.u. This is a fast El transition and indicates a reflection asymmetric shape for ^{223}Ac . The observed levels and γ -ray branching ratios are in good agreement with the results of a theoretical calculation which includes octupole deformation in the potential.

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- j. Shell-model States Around $Z = 64$ and $N = 82$ (M. Quader,* P. J. Daly,* Z. W. Grabowski,* W. Trzaska,* R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, and M. W. Drigert†)

The main aim of this research program is the investigation of nuclei close to $N = 82$ and $Z = 64$ in order to test the applicability of the shell model in this region. Shell-model calculations, using ^{146}Gd as a closed core have been extremely successful previously in describing the low-spin level structure in this region.

This year advantage was taken of the BGO gamma-ray facility to study in great detail to the highest spins and excitation energies the nuclei ^{150}Er and ^{149}Ho . The excellent sensitivity provided by the instrument makes it feasible to extend greatly the level schemes obtained in our earlier studies. We note that ^{150}Er is the counterpart in the rare-earth region of ^{212}Rn , a nucleus with 4 valence protons outside a ^{208}Pb core. The well-studied level scheme of ^{212}Rn is often the showpiece chosen a) to illustrate the generation of high-angular momentum in nuclei by successive alignment of the orbital motions of individual nucleons and b) to test the predictive power of various calculations. Considering target availability and fission competition, ^{150}Er would appear to be a much more favorable case than ^{212}Rn for studying high-spin states in heavy-ion-induced reactions.

The reactions $^{92}\text{Mo}(^{60}\text{Ni}, 3p)^{149}\text{Ho}$ and $^{92}\text{Mo}(^{60}\text{Ni}, 2p)^{150}\text{Er}$ were used at a beam energy of 255 MeV. The data were obtained with 8 Compton-suppressed Ge detectors and 14 elements of the BGO array. Coincidence events were recorded to tape for off-line analysis. The experimental setup also allowed detection of isomers. This facilitates the channel identification, and also gives complementary information. The analysis of this experiment is currently in progress. At this point one can state that in both nuclei the yrast sequence was followed up to an excitation energy of ~ 11 MeV. The observed level structure is irregular as is expected in the particle-alignment picture. At the moment the analysis focusses on the angular correlations that can be extracted from the data taken at different angles. This information is essential to establish the spin and parity of the observed levels.

In order to obtain spin and parity information for some of the low-lying states studied in earlier experiments (these quantities have often been

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assigned tentatively by relying heavily on shell-model considerations) another experiment was performed with the recently-installed Purdue superconducting electron spectrometer. The conversion electrons from states populated after the decay of long-lived isomers ($t_{1/2} > 10$ ns) in ^{149}Ho and ^{150}Er were studied using the recoil-shadow technique. Here the target is located upstream of the spectrometer and the recoiling product nuclei are collected on a Be catcher foil at the center of the spectrometer. For this experiment a ^{122}Te target was irradiated with a ^{32}S beam of 160 MeV. Very clean data were obtained which are currently under analysis. Further experiments with the electron spectrometer are planned in the near future. They will again emphasize the measurement of multipolarities of transitions in nuclei around ^{146}Gd in order to establish firmly spins and parities of the aligned-particle states.

- k. Electromagnetic Transitions in Neutron-rich Nuclei in the $A \approx 40$ Region via Reactions of ^{36}S with ^9Be (R. L. Kozub,* J. F. Shriner,* M. M. Hindi,* R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, M. W. Drigert,† U. Garg,† and J. J. Kolata†)

The BGO γ -ray facility at ATLAS was used in conjunction with charged-particle detectors to test the feasibility of observing, in triple coincidence, the emission of two charged particles and a γ ray from neutron-rich systems.

A small, cylindrical chamber (8.4-cm diameter $\times$ 7.5-cm high) which fits in the small cavity formed by the CSG's and BGO elements was designed and constructed to contain the target, magnets for electron suppression, a collimator, and two E-AE Si(SB) detector telescopes. In December 1986, a first experiment was performed.

The target consisted of a 2.34-mg/cm²-thick Be foil with 10 mg/cm² of Pb evaporated onto the downstream side to stop most of the heavy reaction products. An additional Pb foil of 7.5-mg/cm² thickness served to stop the ^{36}S beam, which had an energy of 100 MeV upon entering the target. The E-AE telescopes were placed in the forward direction at $\pm 13^\circ$ to detect light particles ($Z < 3$) which had enough energy to penetrate the beam stopper foil and the 40- μm -thick AE detectors. Each telescope subtended a solid angle of

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0.14 sr. Three of the CSG's were positioned at $\pm 90^\circ$ with respect to the beam axis while the other four were positioned at $\pm 146^\circ$. Energy and timing information from all CSG's and the telescopes and the multiplicity of BGO signals were recorded for all two-fold or higher-order coincidences among the CSG's and telescopes.

Sorting of the data was performed at Tennessee Technological University. Spectra of γ rays emitted in coincidence with protons, deuterons, tritons, and α -particles have been obtained. From these spectra, it is clear that the most prominent reaction channels in which a charged particle is evaporated are p,n (leading to ^{43}K), p,2n (leading to ^{42}K), and α ,n (leading to ^{40}Ar). We thus expect new structure information on these neutron-rich potassium isotopes to be revealed when the data are sorted in the γ - γ coincidence mode.

Spectra of γ rays emitted in coincidence with two charged particles ($\alpha\alpha,\gamma$) and ($\alpha p,\gamma$) have also been obtained. Two transitions which may be attributed to ^{37}S are observed, as well as four lines which can be attributed to ^{40}Cl with a high degree of confidence. A preliminary decay scheme for ^{40}Cl has been derived. Our proposed levels agree quite well with those deduced from earlier charge-exchange work, and the number and spacing of low-lying states would seem reasonable, based on the weak-coupling picture (see Fig. I-16).

A second experiment was performed in July 1987. In this case, the 100-MeV ^{36}S beam irradiated a ^7Li target. The setup was identical to the one used in the previous experiment. The analysis of this run is still in progress.

Fig. I-16. Suggested decay scheme for transitions in ^{40}Cl . Preferred spins are shown in brackets ([]), but these are not to be viewed as assignments. Also shown are low-lying levels observed by Fifield et al. and a prediction of Woods (Interaction I). The predicted states with a large direct overlap of the ^{37}Cl ground state coupled to the ^{43}Ca ground state are marked with an asterisk (*). Interaction II of Woods results in a similar ordering for the lowest levels.

1. Lifetime Measurements in $^{187,189,191}\text{Tl}$ (K. B. Beard,*
M. W. Drigert,* L. Goettig,* A. Morsad,* U. Garg* I. Ahmad,
R. Holzmann, R. V. F. Janssens, T. L. Khoo, and W.-C. Ma,)

The structure of the light-mass $\text{Tl}(Z = 81)$ nuclei has been a puzzle ever since the discovery of strongly-coupled bands built on $9/2^-$ states in these single-proton-hole nuclei near the $Z = 82$ closed shell. These bands are now viewed as one of the best-known families of shell-model intruder states. An often-noted feature of these bands has been the remarkably constant level spacings over a wide range of Tl nuclei, whereas the $9/2^-$ state itself "plunges" in excitation energy with decreasing mass number -- the apparent increase in deformation indicated by this plunge in energy was not consistent with the constant moments of inertia indicated by the similar band spacings. In a recent laser hyperfine structure (LHS) measurement, however, it was found that the quadrupole moments of the $9/2^-$ states do change with mass number; the constant moments of inertia were sought to be explained in terms of a compensating contribution from pairing.

With a view to attempting to solve this puzzle in a direct way, we decided to measure the lifetimes for the members of the $9/2^-$ bands in a number of light-mass Tl nuclei, the basic idea being that from the $B(E2)$ values extracted from these measurements, it would be possible to obtain the quadrupole moments independent of the assumptions inherent in the LHS measurements.

The lifetime measurements were performed using the recoil distance technique following the $^{159}\text{Tb}(^{32,34,36}\text{S}, 4n)^{187,189,191}\text{Tl}$ reactions. The various S beams were provided by the ATLAS facility. The Argonne plunger apparatus was used in conjunction with the Argonne/Notre Dame gamma-ray facility. A total of 6 Compton-suppressed Ge detectors and a 14-element BGO array was used, the latter as a multiplicity filter to allow selection of high-spin states and elimination of contributions from Coulomb excitation and radioactivity from the final spectra.

Data were taken at several target-to-stopper distances between $\approx 20\text{ }\mu\text{m}$ and 3 mm for all three reactions; the rolled Tb target ($\approx 800\text{-}\mu\text{g}/\text{cm}^2$ thick) made it difficult to achieve any smaller distances. In the 3 nuclei under study, all the known γ rays exhibit a rather long lifetime component (estimated from

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a preliminary analysis of the data to be ≈ 350 ps). This long-lived isomer was completely unexpected and made it impossible to extract the lifetimes of the band members (expected to be in the few ps range). On the other hand, the isomer itself is quite intriguing and its nature remains to be explored. Since we observe this isomer in all three isotopes, in each case with a mean lifetime of > 300 ps, it appears to be a general property of these light-mass Tl nuclei. One possibility is that these might be the "unusual" K-isomers recently suggested in the light-mass Tl nuclei; if so, this could have very interesting theoretical implications. In any event, it is imperative to locate the "position" of these isomers and to further investigate their nature. As a first step towards that end, we propose to do complete γ - γ coincidence measurements for these nuclei to extend the level schemes to higher spins.

D. ACCELERATOR MASS SPECTROMETRY (AMS)

Since last year, the AMS program at ATLAS has focussed on two long-range projects: (i) the development of a radiocalcium dating method utilizing the cosmogenic radioisotope ^{41}Ca ($t_{1/2} = 1.0 \times 10^5$ yr); and (ii) the detection of the anthropogenic fission product ^{126}Sn ($t_{1/2} \approx 10^5$ yr). Both projects take advantage of the ATLAS system which provides a perfect isotopic filter through the velocity-focussing rf structure of the linac, and boosts the energy of the ions to a level where an excellent isobaric separation with the newly-developed method of a gas-filled magnetic spectrograph can be achieved.

Radiocalcium was proposed many years ago as a potential candidate for dating bones in the range of 0.1 to 1 million years, thus extending the time range accessible to radiocarbon dating ($< 50,000$ years) by more than one order of magnitude. In 1986 we detected for the first time ^{41}Ca in a contemporary cow bone at a level of $^{41}\text{Ca}/\text{Ca} = 2.0 \times 10^{-14}$. However, this was only possible with the help of an elaborate isotopic enrichment process prior to the AMS measurement. Efforts to improve the efficiency of the AMS method to a level where the extremely low ^{41}Ca concentrations can be measured directly with AMS have been pursued successfully in the past year. First measurements of ^{41}Ca in several ^{14}C -dated bone specimens have been started.

The long-lived fission product ^{126}Sn has been measured in the tin fraction extracted from spent fuel rod material of a nuclear power plant. Adding a substantial amount of stable tin carrier, ratios of $^{126}\text{Sn}/\text{Sn}$ in the 10^{-7} range have been measured. This is the heaviest radioisotope detected with AMS at ATLAS so far. A new method of running ATLAS for the detection of ^{126}Sn at the much lower concentrations to be expected from environmental samples has been developed.

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

Recently, P. Sharma and R. Middleton¹ from the University of Pennsylvania reported $^{40}\text{CaH}_3^-$ beams of several microamps produced with a high-intensity cesium sputter source using CaH_2 as source material. If negative ion currents of this magnitude can be obtained from CaH_2 prepared from real samples at the entrance of the ATLAS accelerator, it will be possible to perform $^{41}\text{Ca}/\text{Ca}$ measurements at natural terrestrial levels. Although the use of CaH_2 as source material imposes substantial preparatory problems because of the reactivity of the material, the advantages for a very sensitive ^{41}Ca detection are outstanding. The overriding problem in AMS measurements is the interference from the stable isobar. Since $^{41}\text{KH}_3$ does not form stable negative ions, the use of $^{41}\text{CaH}_3^-$ ions greatly suppresses the otherwise overwhelming interference of ^{41}K .

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¹P. Sharma and R. Middleton, Nucl. Instrum. Methods B29, 63 (1987).

First we tried to improve the output from our SNICS ion source (Source of Negative Ions by Cesium Sputtering) reaching a marginal 1 microamp of $^{40}\text{CaH}_3^-$ at a teststand and 0.4 microamps at the ATLAS injection point. Since test runs at the University of Rochester tandem facility with a second generation SNICS source developed by NEC showed very promising $^{40}\text{CaH}_3^-$ currents, we decided to purchase the same source. This source easily delivered 2 microamps of $^{40}\text{CaH}_3^-$ at our test stand. In the first run with Ca samples extracted from bone we achieved $^{40}\text{CaH}_3^-$ beams of 1 to 1.5 microamps at the injection point of ATLAS. Typically, 50 mg of CaO is needed to prepare suitable CaH_2 samples for the sputter source.

- b. Direct Measurement of $^{41}\text{Ca}/\text{Ca}$ Ratios in Bone Calcium (M. Paul,* I. Ahmad, P. J. Billquist, B. G. Glagola, W. Kutschera, R. Pardo, K. E. Rehm, J. L. Yntema, W. Henning,** R. E. Taylor,† and P. J. Slota†)

With the improvement in CaH_3^- beam current (cf. Sec. D.a.), it was possible to perform a first experiment to measure $^{41}\text{Ca}/\text{Ca}$ ratios in bone calcium without isotopic pre-enrichment. The experimental setup was similar to the one described in Henning et al.¹ ^{41}Ca ions accelerated to 200 MeV with ATLAS were analyzed and counted in the gas-filled (8 torr nitrogen) Enge split-pole spectrograph. For this purpose ATLAS was tuned with $^{36}\text{S}^{7+}$ ions in a similar way as described in Sec. D.d. Currently, we have reached a detection sensitivity for $^{41}\text{Ca}/\text{Ca}$ ratio measurements of 1×10^{-15} , corresponding to the counting of one ^{41}Ca ion per hour in the spectrograph.

Preliminary measurements on three ^{14}C -dated bone samples from tar deposits (post-mortem changes are expected to be small in such an environment) showed ^{41}Ca signals in the range from 10^{-15} to 10^{-14} . Interpretation of $^{41}\text{Ca}/\text{Ca}$ data for reliable age determination will depend on a detailed understanding of all processes affecting these ratios, some of which are discussed in Sec. D.c.

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¹W. Henning, W. A. Bell, P. J. Billquist, B. G. Glagola, W. Kutschera, Z. Liu, H. F. Lucas, M. Paul, K. E. Rehm, and J. L. Yntema, *Science* **236**, 725 (1987).

c. Estimate of the Natural Production of ^{41}Ca on Earth (K. Furer and W. Kutschera)

The ability to detect ^{41}Ca at natural levels with AMS is a necessary but not sufficient condition for developing a radiocalcium dating method. In particular, the natural production of this radioisotope must be understood in great detail. Compared to radiocarbon, which is almost exclusively produced through the $^{14}\text{N}(\text{n},\text{p})^{14}\text{C}$ reaction in the atmosphere and distributed into the various terrestrial reservoirs as CO_2 , radiocalcium is mainly produced in situ through the $^{40}\text{Ca}(\text{n},\gamma)^{41}\text{Ca}$ reaction. This leads to a much more complex production mechanism and a reliable dating can only be achieved if the various sources of neutrons at the site of the sample are understood.

In a preliminary investigation of this problem, we have estimated the following production mechanisms of ^{41}Ca : (i) $^{40}\text{Ca}(\text{n},\gamma)^{41}\text{Ca}$ reactions induced by cosmic-ray secondary neutrons near the surface of the Earth, This is considered to be the main production mechanism and leads to a $^{41}\text{Ca}/\text{Ca}$ ratio in the high 10^{-15} range. (ii) The second largest source of neutrons in the lithosphere seems to come from cosmic-ray muons. We have estimated the contribution of neutrons generated by stopped negative muons and found that the corresponding ^{41}Ca production can be as high as ten percent of that from atmospheric thermal neutrons. (iii) Another source of neutrons comes from the natural uranium and thorium content in rocks through (α,n) reactions or spontaneous fission neutrons of ^{238}U . At normal uranium and thorium concentrations (i.e. in the ppm range), this contribution is at least two orders of magnitude smaller than the one from cosmic-ray neutrons. (iv) Spallation of atmospheric krypton by cosmic rays was estimated to give a negligible source of ^{41}Ca .

There are additional production processes not yet considered, which may or may not contribute significantly to the ^{41}Ca inventory on Earth, such as reactions of solar flare ^3He and ^4He particles on atmospheric argon. Examples are $^{40}\text{Ar}(^3\text{He},2\text{n})^{41}\text{Ca}$ and $^{40}\text{Ar}(^4\text{He},3\text{n})^{41}\text{Ca}$.

- d. AMS Measurements of ^{126}Sn at ATLAS (W. Kutschera, I. Ahmad, P. J. Billquist, B. G. Glagola, K. J. Jensen, R. C. Pardo, K. E. Rehm, J. L. Yntema, M. Kaba,* and M. Paul†)

The detection of the long-lived fission product ^{126}Sn at low levels with AMS pushes the current mass limit of the ATLAS system. Originally, it was planned to perform a new measurement of the poorly-known half-life of ^{126}Sn ($t_{1/2} \approx 10^5$ yr), utilizing material extracted from spent fuel rods of the Zion nuclear power plant in Illinois. Measuring both the activity (with gamma-ray spectroscopy) and the number of ^{126}Sn atoms (with AMS) in the material, the decay constant can be obtained from the well-known relation $dN(^{126}\text{Sn})/dt = -\lambda \cdot N(^{126}\text{Sn})$. Although we could easily detect ^{126}Sn with a counting rate of about one hundred per second in the gas-filled split-pole spectrograph, a reliable $^{126}\text{Sn}/\text{Sn}$ ratio could not be obtained due to interference from multiple charge-state components when the current of the stable tin isotopes was measured for normalization (the ions are stripped twice in the tandem terminal and before the 90-degree analyzing magnet). Since the material on hand has been thoroughly purified and has a relatively high $^{126}\text{Sn}/\text{Sn}$ ratio (in the range from 10^{-7} to 10^{-6}), an isotopic ratio measurement with low-energy mass spectrometry in collaboration with G.J. Wasserburg at CalTech is planned. Together with our activity measurement it is expected to get a new half-life value of at least 10% accuracy.

In order to push the ^{126}Sn detection with AMS below the 10^{-10} range, we have developed a new tuning procedure of ATLAS avoiding the stable isobar ^{126}Te for this purpose. It was demonstrated that the linac can be tuned perfectly for $^{126}\text{Sn}^{26+}$ ion acceleration with the non-isobaric ion $^{107}\text{Ag}^{22+}$, if these ions are injected with the same velocity. The latter condition can easily be achieved by a corresponding adjustment of the tandem voltage. Since the charge/mass ratios of these ions are the same within 3.5×10^{-3} , the magnetic rigidity is also the same and the high-energy beam line system can also be accurately tuned. With this condition it was possible to reduce the ^{126}Te background to about 1 ppb (10^{-9}), which makes it quite possible to measure ^{126}Sn as low as 10^{-11} , considering the discriminatory power of isobar separation in the gas-filled spectrograph at 400-MeV energy (see Fig. I-17).

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Fig. I-17. Detection of ^{126}Sn in the gas-filled spectrograph. Spectrum (a) was measured after tuning ATLAS with ^{126}Te and (b) after ^{107}Ag was used for the same purpose.

- e. Monte Carlo Calculations for Isobar Separation in the Gas-filled Enge Split-pole Spectrograph (B. Schneck, W. Kutschera, K. E. Rehm, M. Paul,* and W. Henning†)

Heavy ions moving swiftly through a gas-filled magnetic region follow a trajectory which is determined by their mean charge state, which in turn is determined by the velocity and the atomic number of the ion. In a typical AMS experiment, ions of the radioisotope of interest and of an accompanying background of stable isobars arrive with the same velocity at the final detection system. In spite of indistinguishable mass differences, the ions get well separated in the focal plane of a gas-filled spectrograph due to the difference in mean charge state. The separation is further increased since ions with a higher mean charge state experience a larger energy loss in their passage through the gas.

We have calculated the trajectory of individual ions by integrating the equation of motion with the computer program RAYTRACE, taking into account the ion-gas interactions in a semi-microscopic way. Charge-changing collisions, energy-loss straggling and angular straggling were treated by applying Monte Carlo techniques. The energy loss between charge-changing collisions was calculated from the stopping power tables of Ziegler. Position spectra along the focal plane of the Enge split-pole magnetic spectrograph were calculated by sampling large numbers (300 to 1000) of incoming ions and accumulating their position (x and y) in the detector plane. Very good agreement with experimental results of 300-MeV ^{58}Fe - ^{58}Ni ions and 400-MeV ^{126}Sn - ^{126}Te ions was established, giving confidence that this procedure can be used to predict the properties of isobar separation in a gas-filled magnetic spectrograph for a large variety of isobaric ions and energies.

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E. POSITRONS IN HEAVY-ION COLLISIONS

In anticipation of U beams in 1991, preparation has begun for measurements to ascertain the nature of the intriguing correlated positron-electron sharp lines observed in heavy-ion scattering experiments at GSI.

a. Positron Experiments at ATLAS

Within the next three years, the ATLAS facility will be upgraded so as to provide beams of heavy ions which span the entire range of stable species. One of the most important aspects of this upgrade will be the ability of ATLAS to produce intense beams of the heaviest ions, such as uranium. This will open up the possibility of studying the physics of extremely high-Z quasi-atoms formed in the collisions of these very heavy ions. Experiments of this type have hitherto only been possible at the UNILAC accelerator at GSI, Darmstadt and at the SuperHILAC, Berkley, and have led to the discovery of a very puzzling phenomenon in heavy-ion physics; namely the observation of unexpectedly narrow lines in the spectra of positrons produced in collision systems such as $U + U$. This result is not even qualitatively understood at the present time and explanations ranging from the formation of giant nuclear molecules to the decay of a previously unknown elementary particle have been proposed. The study of this and related phenomena will be an important new area of study for the upgraded ATLAS accelerator.

In order to begin planning, we have initiated a number of discussions and investigations, with the aim of arriving at a concrete proposal for a new experimental facility. A workshop was held to discuss the current status of the narrow positron lines. Preliminary design studies of a Time Projection Chamber for heavy-ion positrons and of a large solid-angle magnetic spectrometer as well as other options are being performed (see Secs. F.p and F.q). A collaboration with university user groups, particularly at Yale University and Michigan State University, is in the formative stages. An experiment to search for two-photon decaying elementary objects, similar to that reported recently but with the heaviest beams from ATLAS, will be carried out in Spring 1988.

b. Positron Workshop (R. R. Betts and J. P. Schiffer)

A three-day workshop on "Future Experiments at ATLAS to Study Positron Production in Heavy-ion Reactions" was held November 30 - December 2 at Argonne. The aim of the workshop was to survey the current status of the sharp positron lines observed in heavy-ion experiments and also to review searches for similar phenomena in other types of experiments. The Workshop was attended by some 60 scientists representing not only the traditional heavy-ion physics community but a wide range of sub-areas of nuclear, atomic and particle physics. The latest results from the major experiments at GSI were presented and extended discussion of the technical aspects of these experiments took place. We are now in the process of digesting all this information and considering the options open for a future experiment at ATLAS.

c. Search for 180-degree Correlated Equal-energy Photons (R. R. Betts, R. V. F. Janssens, T. F. Wang, R. W. Dunford, T. L. Khoo, B. B. Back, H.-J. Körner, and G. Rathke)

Following the recent report of the observation of 180-degree correlated equal-energy photons from 5.9-MeV/nucleon U + Th collisions, we plan to perform a similar experiment for a lighter system $^{93}\text{Nb} + ^{238}\text{U}$. The observation of a sharp line in the two-photon spectrum of such a light system would either extend the region of $Z_1 + Z_2$ for which such phenomena occur to one far below current expectations or suggest that the processes which produce the sharp peaks in the two-photon spectra are different from those producing the sharp positron lines.

The experiment will be carried out using the Argonne-Notre Dame BGO-CSS array and estimates of the expected count rates suggest that useful limits can be set on the cross section for producing such objects in a reasonably short period of beam time. The experiment will be carried out in the Spring of 1988.

- d. Search for Positron Resonances in the Interaction of Positrons with Electrons (I. Ahmad, S. J. Freedman, R. V. F. Janssens, J. P. Schiffer, and T. F. Wang)

Reports from GSI about sharp positron lines from collisions between uranium or other heavy nuclei continue to persist. With the completion of the ATLAS uranium upgrade still in the future it is important to investigate the possibility by other techniques that this phenomenon might conceivably be the consequence of a neutral resonance which decays into an electron-positron pair. Such a resonance may then be observable in low-energy $e^+ - e^-$ scattering experiments.

Recently there has been a published report¹ that with a source of ^{68}Ge - ^{68}Ga (whose decay does not provide sufficient positron energies to make such a resonance on free electrons), a Th scattering foil, and two mini-orange spectrometers viewing the scatterer with an angle of separation of 90 degrees, a line has been observed that roughly matches the characteristics of the GSI data. It is kinematically possible that bound electrons in the thorium atom provide enough momentum to form such a resonance. We attempted a similar measurement with two mini-orange spectrometers, viewing a source and scatterer from opposite sides (180 degrees apart). Bhabha scattering from free electrons will be reduced in this geometry, but the decay of a neutral resonance almost at rest will produce a better signature. After collecting enough statistics compared to that in the published report, we have found no evidence of a line structure as claimed in the report. A paper describing our work has recently been published.

¹K. A. Erb, I. Y. Lee, and W. T. Milner, Phys. Lett. B 181, 52 (1986).

F. EQUIPMENT DEVELOPMENT AT THE ATLAS FACILITY

Effective research with a new accelerator requires construction of equipment which are well-matched to the capabilities of the machine. In the past year, the three major experimental facilities at ATLAS (large scattering chamber, multi-crystal gamma-ray facility and split-pole spectrograph) were completed according to their original concepts. In addition, new equipment was developed expanding the capabilities of these facilities considerably. This includes a large-area time-of-flight system for the scattering facility, a new scattering chamber for the gamma-ray facility to perform particle-gamma coincidence experiments, a new focal-plane detector and addition of particle-gamma coincidence capability for the split-pole spectrograph. Furthermore, the superconducting electron spectrometer developed at Purdue was installed and successfully tested at ATLAS. The Fragment Mass Analyzer (FMA) project is in full swing after it was approved by DOE in June 1987. The final optical design has been fixed and construction of the FMA has started. When completed in two years, the instrument will be an important new tool for experiments with the upgraded ATLAS facility. The data-acquisition system has been fully upgraded to modern computers after the PDP 11/45 in the Area II Target Room was replaced by a MicroVAX II.

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

The Fragment Mass Analyzer (FMA) proposal was approved in June 1987. Shortly thereafter a final design study was begun, in response to suggestions from referees of the proposals, with the aim of finding the best configuration of electric and magnetic elements consistent with our scientific needs and budgetary and space constraints. During the course of this study, 5 possible devices were subjected to a thorough ion-optical investigation. The final device chosen is quite similar to the originally proposed FMA, except for the addition of another quadrupole doublet at the end (see Fig. I-18). This quadrupole is placed so as to complete the symmetry about the center of the magnet. The result is improved vertical focussing (90% of the ions lie within a 1-cm region) and somewhat improved mass resolution.

The FMA will also be located in a new target area, which will be built adjacent to Target Area III. The size of this addition will be 50 ft. x 50 ft., providing enough room for the FMA and at least one other major installation. The FMA support structure has been designed to allow for radial motion as well as angular rotation. This will allow the distance

*Special term appointee.

Fig. I-18. Layout of the Fragment Mass Analyzer (FMA) currently being developed at ATLAS. Visible are the two electric dipoles and sector magnet as well as other focussing elements.

between the target and the first quadrupole of the FMA to be varied. Moving back will permit large detector arrays at the target, while moving closer will give a larger solid angle.

On September 10, 1987, an FMA Review Panel was convened, consisting of J. Kolata (Chairman, Notre Dame), J. Hamilton (Vanderbilt U.), J. Nolen (MSU), S. Steadman (MIT), and R. Vandenbosch (U. of Washington). This group reviewed the plans for the FMA, including ion optics, space, optimization to the ATLAS scientific program, experimental facilities, and involvement of outside users. The panel was favorably impressed with the FMA, and urged that it be completed on a timely basis.

On September 21-22, 1987, an FMA Workshop was held at ANL, with about 60 attendees from Europe, Asia, and the United States. In addition to a description of the FMA, invited speakers from laboratories with similar facilities surveyed current research with their devices. Three working groups were then formed, dealing with the target area, the detector area, and construction and operation. Very enthusiastic discussions occurred in all groups, with a number of users expressing interest in including the FMA in their future research plans and in participation in aspects of its construction.

Currently we are engaged in three major areas: preparation of bid packages for the major electric and magnetic elements, design of the support structure, and development of prototype high-voltage power supplies for the electrostatic dipoles. We hope to place orders for the long-lead-time items in early 1988. Beam tests of the power supplies and mock electrodes are also scheduled for early 1988.

b. Development of Vacuum-mounted High-voltage Power Supplies for the FMA
(C. Davids, J. Bogaty, B. Nardi, and W. Kutschera)

Two prototype 300-kV power supplies have been constructed for use with the electrostatic deflectors of the FMA, one of each polarity. They each consist of a 30-stage Cockroft-Walton multiplier stack contained in an insulating tube, which is pressurized with sulfur hexafluoride gas. A commercial switching-mode power supply is used to control and drive the stack. Both units have been successfully operated in air to the maximum voltage. The positive supply has been operated in the vacuum of the ATLAS 36-inch scattering chamber at a voltage of 275 kV, using an aluminum electrode. No problems were encountered in conditioning the apparatus to this voltage. After testing the negative unit in vacuum, different electrode materials will be used in vacuum tests with both supplies. Following this will be a beam test, where mock electrodes will be bombarded with a heavy-ion beam from ATLAS.

c. Design of FMA Focal-plane Detectors (B. D. Wilkins and D. J. Henderson)

A coupling of the Fragment Mass Analyzer (FMA) to the heavy-ion beams available at ATLAS provides a unique research facility not available anywhere else in the world. Advancement of our scientific knowledge using this research device does require, however, the development of state-of-the-art detectors which provide the researcher with the appropriate experimental parameters.

Design for a large-area microchannel-plate detector (6 cm x 2 cm) is beginning. This detector will provide a fast-timing signal ($\Delta t \sim 200$ ps.) for a time-of-flight measurement of the mass-analyzed fragments as well as x and y position information (Δx and $\Delta y \sim 0.5$ mm). A second detector will be needed to resolve the nuclear charge of the typical low-energy fragment obtained from the FMA. A Bragg-curve spectrometer is considered the most likely candidate for this detector. Work is currently underway, using an existing Bragg-curve spectrometer to see if the Z resolution can be extended down below the Bragg Peak to an energy range of 0.5–1.0 MeV/A. A ^{252}Cf spontaneous fission source is used to provide low-energy fission fragments and coincident K X-rays to facilitate this study.

- d. Construction of a Gamma-ray Facility for ATLAS (R. V. F. Janssens, T. L. Khoo, R. Holzmann, U. Garg,* K. Beard,* M. W. Drigert,* and P. Wilt*)

The construction of a gamma-ray facility, which consists of (a) a 4π gamma-sum/multiplicity spectrometer with 50 hexagonal BGO elements and (b) 12 Compton-suppressed Ge detectors (CSG) external to the hexagonal elements has continued. This project is a collaborative effort between the University of Notre Dame and Argonne. This project is now very close to completion. During the last year the following activities were performed:

-- All detectors for the array have been tested and assembled. The energy resolution of all regular hexagonal detectors was found to be better than 16% for the 661-keV line of ^{137}Cs . The "special" detectors (i.e., the irregularly shaped detectors of the outer ring and the hexagonal detectors with special holes which allow gamma rays to reach the CSG's) all have energy resolutions of the order of 20%.

-- The following electronics modules were constructed at Notre Dame: Camac-controlled Constant Fraction Discriminators, Dead-time Generators and Analog Delays.

-- Construction of Logic Delay Units and of a Camac unit for decoding the gamma-ray multiplicity is expected to be completed early in 1988.

-- The remaining CSG's (i.e., units 8-12) have been tested. Their properties regarding suppression and resolution were found to be similar to those of all units purchased earlier.

-- All detectors have been installed at ATLAS in September and the accompanying electronics was tested.

-- A spare Ge detector has been ordered.

First experiments with the full detection system have been conducted successfully in December.

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- e. Detector Design Studies for National Gamma-ray Detector and Proposal Preparation (I. Ahmad, H. Esbensen, M. Haas, R. V. F. Janssens, and T. L. Khoo)

There is intense interest in the nuclear structure physics community for a National Gamma-ray Detector and a proposal for this device is being prepared for submission to DOE. It is envisaged to consist 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.

A large community of physicists have been engaged in activities related to the preparation of the proposal. The group at Argonne has taken the lead role in assembling the justification section of the proposal and actively participated in design studies of the detector system and associated acquisition system.

We have undertaken to design, develop and construct a prototype detector module, consisting of a large n-type Ge detector and BGO elements for the suppression shield. This activity is being supported by the Laboratory Director's Exploratory Research Funds. We are also collaborating with physicists at the University of Notre Dame on Monte-Carlo calculations of detector response, in order to decide on the optimum detector configuration.

The Physics Division fully supports the National Gamma-ray Facility. ATLAS, which will have the capability to produce both the lightest and heaviest beams, is the ideal accelerator to couple to this facility and space can be made available in the new Target Area IV.

- f. Measurement of the Response of the Hexagonal BGO Detectors of the BGO Gamma-ray Facility to 5-50-MeV Mono-energetic Gamma-rays
 (R. V. F. Janssens, R. Schmidt,* J. V. Kratz,* H. Emling,† H. Grein,† E. Grosse,† W. Henning,† N. Herrmann,† R. Kulesa,† R. Freifelder,† T. Matulewicz,† R. S. Simon,† H. J. Wollersheim,† B. Schoch,‡ J. Vogt,‡ and M. Wilhelm‡)

For a variety of scintillator materials and solid-state detectors the response to mono-energetic photons in the 5-50-MeV energy range is rather poorly known. This region is of great current interest in view of recent results on the gamma decay of giant resonances built on high-spin states and on other very high-energy gamma-rays emitted in heavy-ion-induced reactions, for example.

At the tagged photon facility of the MAMI electron microtron at Mainz, we measured the response of a variety of detectors, i.e. hexagonal BaF₂ counters (5-cm face-to-face and 20-cm long), 3*3 inch CsI, a set of 5 lead-glass detectors (3-cm face-to-face and 35-cm long), a Compton-suppressed Ge detector (the suppressor shield being of BGO, the Ge assembly being made of 3 Ge detectors mounted back to back for improved suppression), a 5*5 inch NaI(Tl) detector (used for reference) and 6 hexagonal BGO detectors from the Argonne/Notre Dame gamma-ray facility. For the hexagonal detectors the set-up consisted of a central detector surrounded on each face by another detector of the same type. The central detector was irradiated with 5-50-MeV tagged photons and the response was measured. The energy collected in the side detectors was also recorded so that the Compton-scattering probability can also be obtained. Finally, the side detectors were also briefly exposed to the direct beam in order to ensure that their response is similar to that of the central counter. The results of all the measurements are currently under analysis. Comparisons with Monte Carlo calculations with the code GEANT are also planned.

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

A large particle scattering chamber is being constructed for running particle γ coincidence experiments at the Argonne γ -ray facility. This chamber will make it possible to obtain high-quality particle spectra, with good angle and time-of-flight resolution, in coincidence with γ -rays detected in the array. The vacuum vessel and mounting framework have now been completed and will soon be put in place. Work on the internal hardware (target assembly, detector mounts, etc.) is also almost finished. A large number of experiments have already been proposed for this chamber and it is expected that these will be scheduled for early this year. Initial design work has begun on an extension to the chamber which will allow several large gas counters to be mounted within the vacuum vessel. It is anticipated that this extension will also be ready early in 1988.

h. Test of BaF_2 Crystal for Gamma-ray Spectroscopy (I. Ahmad,
T. L. Khoo, and D. Williamson,*)

We have tested a 6.5-cm x 6.5-cm BaF_2 crystal with the aim of using it in a BGO anti-Compton shield. The detector was obtained from Harshaw and it was coupled to a 3-in Thorn EMI model 9821QB04 photomultiplier tube. The energy and time resolution of the system was measured at several high-voltage values. For a ^{60}Co source the time resolution (FWHM) was 500 ps with the threshold at 100 keV and the energy resolution for ^{137}Cs gamma-ray was 11%. We plan to place this detector in a BGO anti-Compton shield and use it for the measurement of high-energy gamma rays. Because of the fast timing of this detector, it will be possible to separate the neutrons from gamma rays. We are also testing small BaF_2 crystals for low energies (50-200 keV) in order to use them in level lifetime measurements.

*Co-op student from University of Illinois, Chicago (deceased).

i. ATLAS Scattering Chamber Facility (D. G. Kovar, J. Falout, and B. Nardi)

The ATLAS scattering chamber came into operation in May 1985 with the first ATLAS beams. Since that time 35 experimental runs, using 112 days of beam time, have been performed. It has proved to be a reliable and flexible general-purpose scattering-chamber facility. Effort continues to expand the chamber's capabilities and improve the ease and efficiency of making measurements. Power and cabling capabilities to satisfy larger experimental setups have been added. The computer control and monitoring for the facility have been enhanced. Expansion of these capabilities to handle large detector arrays will be implemented in the next year.

j. A Large-area Time-of-flight System for the ATLAS Scattering Chamber (B. D. Wilkins, D. J. Henderson, D. G. Kovar, and B. G. Glagola)

A large-area time-of-flight system has been used successfully on a number of experiments at the ATLAS scattering chamber during this past year. Most of the development work on this detector system was completed last year (see last year's report). The new configuration for the large-area (8 cm x 10 cm) avalanche detector, described in last year's report, achieves a timing resolution of 180-190 ps. for heavy ions at low pressures (2 Torr) of isobutane if sufficient care is taken to correct for the rather complex behavior of the x and y position walk. At these low pressures of isobutane efficiency problems arise in this detector around $Z = 6$ which can readily be solved by increasing the gas pressure. This can only be achieved, unfortunately, at the expense of reduced timing performance.

Further development work with the Bragg-curve Spectrometer (BCS), used as the second detector in this time-of-flight (TOF) system showed that this detector can resolve very well the charge, Z , of the heavy fragments if used in the ΔE mode. This is achieved by correlating the TOF information obtained from the avalanche detector with the ΔE signal from the BCS. Thus at low gas pressure (isobutane) one can get good charge resolution from 10 MeV/A $\rightarrow$ 1 MeV/A.

- k. Measurements of Pulse-height Defects and Plasma Delay Effects in Silicon Detectors (D. G. Kovar, D. J. Henderson, B. D. Wilkins, M. A. McMahan,* and G. J. Wozniak*)

The use of silicon detectors to provide accurate energy and timing information in heavy-ion studies requires knowledge of how the observed signals are related to the actual deposited energies and arrival times of the heavy ion. It is well known that the observed energy signals display a pulse-height defect (PHD) and the observed timing signals a plasma delay (PD) which depend on the energy and Z of the detected heavy ion as well as on the characteristics of the detector itself. Insufficient data exist to establish reliably the PHD and PD dependences over the energy ranges and ion species of interest in studies today. The data that do exist are for silicon-surface-barrier- or partially-depleted fission detectors with essentially no results for a number of other silicon detectors that have come into use in the last few years. No results exist today which establish a correlation between PHD and PD.

Measurements of PHD and PD effects in five different kinds of silicon detectors (i.e., surface-barrier, partially-depleted fission, diffused-junction, ion-implanted, and lithium-drifted silicon detectors) were performed at the 88-inch LBL cyclotron using the positive-ion ECR source. Beams of ions were tuned into the scattering chamber where sequentially the Si detectors were rotated into the beam for the measurement. The plasma delay measurements used a microchannel plate detector with a thin C foil located approximately 80 cm upstream of the Si detectors as the start detector. The energy and timing responses of ions of ^{18}O , ^{36}Ar , ^{40}Ar , ^{63}Cu , and ^{86}Kr at 5-6 energies in the energy range $0.5 < E_{\text{lab}} < 10$ MeV/u were measured. Significantly different PHD effects were observed on line for the different detector types. The data are presently being analyzed and will be compared to the parameterizations proposed in the literature.

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l. Development of a Plastic Phoswich Detector for use at ATLAS
(B. D. Wilkins, D. J. Henderson, and D. G. Kovar)

As one enters into increasingly higher energy regimes, heavy-ion reactions become more complex with ever more particles being emitted. To study these reactions a large solid-angle detector system, which has both a high multiplicity capability and good particle identification, becomes a vital part of the necessary experimental equipment.

Several different designs for this system are being considered. A prototype of one element of this system, a plastic phoswich detector, has been designed and constructed. This phoswich detector contains three separate plastics (fast: thickness = .009", slow: thickness = .100", and fast: thickness = 1.00") so that the range of particle identification might be extended. A time-of-flight measurement (using the RF beam timing) will be used to determine the energy of the identified light particles as well as resolve any ambiguities resulting from the use of three different plastics. Position information will be obtained for each particle by comparing the light intensity in two phototubes, one at each end of the phoswich detector.

If this prototype detector proves successful, many elements of this detector can be placed around the target to give a large ($2\pi + 3\pi$) solid-angle coverage for the identification of lighter charged particles.

A beam-line test of this detector is planned in the near future.

m. Modification of the Split-pole Spectrograph for Particle-gamma Coincidence Experiments (K. E. Rehm and J. Goral)

We plan to combine the good particle resolution obtainable from the Enge split-pole spectrograph and its focal-plane detector with the good energy resolution from the Compton-suppressed Ge detectors in experiments that study the interplay between nuclear reaction mechanisms and nuclear structure. For that purpose a frame was added to the split-pole spectrograph which allows the mounting of up to 7 Compton-suppressed Ge detectors close to the target. In addition, a new smaller scattering chamber with thin walls was built, which also allows the mounting of particle detectors in the vicinity of the target. The setup has been installed, aligned and leak tested and will be used in a first experiment in the spring of 1988.

n. The New Focal-plane Detector for the Split-pole Spectrograph
(K. E. Rehm and F. L. H. Wolfs)

For experiments involving medium-mass reaction products a new focal-plane detector system has been built. It consists of a position-sensitive parallel-plate avalanche detector (PPAC) backed by a large Bragg-curve detector (BCD). The total length of the detector is 60 cm. Compared with the previous hybrid detector system the new detector gives better time resolution, higher count-rate capability and better Z-resolution. With this detector, individual isotopes and elements up to the mass-100 region can be separated.

The timing signal obtained from the PPAC has an internal resolution of 250 psec. The PPAC has been operating at count rates up to 20 KHz. The Z-signal is obtained by integrating the Bragg curve in the BCD with a short shaping time, and its resolution measured with Ni and Se particles was found to be $\Delta Z/Z = 1/70$. An example of the Z-resolution obtained from scattering 515-MeV ^{80}Se particles on ^{60}Ni is shown in Fig. I-19. The mass resolution of the detector was measured to $\Delta m/m = 1/150$. The drift time of the Bragg curve in the BCD was used to measure the angle of incidence in the reaction plane. An angle resolution (measured in the focal plane) of $\Delta\theta = 1.4^\circ$ was achieved. The energy resolution measured for 500-MeV ^{58}Ni ions was 0.75% and the position resolution 1.5 mm. The detector was extensively tested with particles ranging from ^4He to ^{80}Se . The whole system was already used in several experiments. A publication is in preparation.

Fig. I-19. Z spectrum from the Bragg curve detector as measured for 515-MeV ^{80}Se on ^{60}Ni .

- o. Superconducting Solenoid Lens Spectrometer (P. J. Daly,*
Z. W. Grabowski,* W. Trzaska,* R. V. F. Janssens, and T. L. Khoo)

The superconducting electron spectrometer developed and tested at Purdue last year was installed at ATLAS last spring. After a period of testing with radioactive sources, a first ^{32}S beam was used for a test experiment in July. During a two-day run several configurations of the spectrometer were tested. Part of the time the Si detector was looking directly at the target. In this mode, delta rays represent a main problem. Several baffles were tested successfully. The spectrometer was also tested in broad and narrow transmission modes. Finally, a set-up where the spectrometer studies electrons from a catcher foil was also investigated. In this so-called shadow method the target is shielded from the detector by a special Pb insert in the spectrometer and the decay of isomers can be studied in a background-free environment. All these tests were very successful. Since then the spectrometer has been used in two experiments.

*Purdue University, West Lafayette, IN.

- p. Development of a Large-area Detector for Multiparticle Coincidence Experiments (R. R. Betts)

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

To improve this we are developing a large-area detector to measure these and similar processes with high (~ 80%) efficiency and excellent energy resolution. Conceptually the device consists of two multiwire gas counters, to measure x, y and to provide time information, backed by a 5×5 -cm silicon microstrip detector for energy and further position information. Monte Carlo

simulation of the breakup of ^{24}Mg following inelastic excitation such as reported by Fulton et al. indicates that this detector will be more than 100 times more efficient and still provide excellent energy resolution. The higher energies of the ATLAS beams will further improve this.

Prototype microstrip detectors are on order and will be tested for position, energy and timing response before combining with the gas counters.

q. A Time Projection Chamber for Heavy-ion Positrons (R. R. Betts and D. Clague*)

Preliminary design studies have been carried out for a large solid-angle tracking detector for positrons and coincident electrons produced in heavy-ion collisions. This detector has the aim of characterizing, as well as possible, the kinematics of the positron and any associated electrons, thus enabling, if it is a two-body decay, a measurement of the invariant mass of the decaying object. The main problems faced in the design of such a device are the large multiple scattering of these low-energy particles and the intense backgrounds due to delta rays, X-rays and the heavy ions themselves. These considerations lead to the choice of either a low-pressure hydrocarbon or He as the counter gas. Monte Carlo simulations of the multiple scattering and track reconstruction lead us to believe that a counter can be made which will give modest momentum ($\Delta p/p = 10\%$ - hydrocarbon gas, $= 3\%$ - He) and excellent angular information for positrons and electrons of interest. The major background problem is the intense flux of low-energy X-rays which are absorbed in the counter window and gas. The estimates of this background are somewhat uncertain at the present due to lack of information on the X-ray production cross sections.

*Summer undergraduate student from the University of Birmingham, Birmingham, England.

r. A Large Solid-angle Orange Type Spectrometer for Electrons and Positrons (R. Dunford, K. E. Rehm and B. Zeidman)

We are exploring the possibility of a large orange-type spectrometer which can simultaneously focus electrons and positrons onto separate focal planes. Information on the angle of emission will be obtained from the time of flight through the spectrometer, utilizing the excellent timing properties of the ATLAS beam. We are currently investigating the feasibility of such a device, in particular its size, which determines the angular resolution and the shape of the field boundaries which determine the size of the focal planes.

s. Nuclear Target Making and Development (J. P. Greene, G. E. Thomas, and G. W. Klimczak)

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

Various targets were produced, either self-supporting or on carbon, gold or stretched substrate backings. Targets produced included $^{10,11}\text{B}$, ^{24}Mg , ^{28}Si , ^{40}Ca , ^{50}Ti , $^{58,60,64}\text{Ni}$, $^{74,76}\text{Ge}$, ^{92}Zr , ^{122}Te and ^{208}Pb . Others were PbSe , CaF_2 , MgO , LiO_2 , UF_4 , SiO_2 and natural Tb . Techniques were developed for the evaporation of thin films of polypropylene and teflon. ATLAS support included producing Fe^{34}S for the ion source as well as carbon stripper foils when needed.

The ultra-clean cryopump evaporator system is routinely producing vacuum in the chamber in the mid- to low- 10^{-8} Torr range after replacement of the compressor unit. This system has been used successfully to sputter some materials. The Veeco Evaporator has been repaired and is currently under high vacuum. This system is designed for simple evaporations. The computer-controlled target storage system is performing well with many targets stored satisfactorily. A second target storage chamber with a new state-of-the-art turbo pump is under development for targets with somewhat less stringent

vacuum requirements. The rolling mill has been tested and some materials rolled. A new controller was installed in the reduction furnace and is performing well. A new inert gas glove box for use with reactive targets has been obtained.

A continued upgrading of present equipment is planned. We have obtained a new quartz crystal monitor with feedthrough for the cryo-pumped sputter source, which now provides all evaporators with thickness monitors. Thermocouple temperature sensors are planned to be installed in the above system as well as the Veeco Evaporator. Work has begun to develop a new target fabrication system which will be dedicated to producing radioactive targets. Possible collaboration with ER Division on the production of thin films for their detector-development program is being pursued, as well as with OHS Division on the metal deposition of electron microscopy samples.

Development and construction of an alpha-thickness monitor for accurate thin-film measurements, increasing our capabilities, has begun. Cost evaluations have been made on both a large state-of-the-art sputtering source and a new highly-focussed electron-beam-gun system. Availability of either of these systems will permit enhanced capabilities for the fabrication of targets, which are not producible with the present equipment. The need for a laminar flow bench has been established, and it is planned that one will be purchased.

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

The VAX 780 (BITNET node ANLPHY) continues to serve as the hub for the Divisional computer resources. It serves as a node on the Argonne DECnet, on BITNET, on HEPNET and as a routing node for the Physics Division DECnet linking 6 VAX's and several PDP's together. A significant increase has occurred in the past year in the use of the 780 for office automation purposes, ...word processing, electronic mail, and calendars.

The reliability of the 780 has been good. Recovery from a disk crash on September 10 was done in 20 hours, reflecting the improved back-up policy implemented as a result of a crash in January 1985, from which it took a week to recover.

An RA60 disk drive and a second TU78 high-performance tape drive have been added to the 780. The single RA60 has not relieved the pressure for more disk space as much as had been hoped. Users offer a variety of excuses for not using the removable packs. Inconvenience is the most probable culprit. Four QMS-800 laser printers presently exist on the VAX's and provide high-quality output from MASS-11, TEX, and plotting packages.

The installation of the site-wide PBX has immensely enhanced the modem capability of the VAX. By placing PBX analog-digital interfaces (ADI's) onto the Equinox DS-5 data switch all Divisional computers are accessible from outside. Since we are now able to use the "modem pool" of ANL we have 9 incoming modems (up from 4) and 3 outgoing (up from 1). Forty terminal ports on the 780 continue to suffice.

A plan is being developed to replace the 780 in the time frame of two or three years. The new generation of VAX's portends the lessening cost effectiveness of the 780.

The three VAX 750s in the Division have functioned well. The DYNAMITRON VAX is routinely used for data acquisition and replay using DAPHNE. The ATLAS VAX serves as the data-acquisition system for two users of the ATLAS accelerator and also serves for replay. The medium-energy VAX serves for analysis of SLAC data and will serve as the host for an ACP ordered recently.

Two MicroVAX II's are presently in the Division. One is used by the medium-energy group for analysis of LAMPF neutrino oscillation data. It presently has 9 MB of memory, a M2333 Fujitsu 337M disk drive, and a Fujitsu M2444AC dual high-density tape drive and a 2-user license. The second is currently in the ATLAS data room and will serve as a DAPHNE acquisition/replay station. It has 16 MB of memory and the same peripherals as is on the first and a 8-user license. The DAPHNE frontend hardware is due to be working before the end of the calendar year. The 11/45 has been moved onto the floor of the data room and serves as a backup.

- u. The Data-acquisition System DAPHNE (L.C. Welch, D. Cyborski, T. Moog, G. Perschbacher, and L. Budrik)

DAPHNE, the data-acquisition system developed for ATLAS, is routinely used. Major enhancements implemented during the past year are scatterplots, histogram manipulation, a FORTRAN cross compiler for the front end, and a plethora of small enhancements and bug fixes. The graphics interface has been speeded up significantly.

- v. SCAMP (S. J. Sanders)

SCAMP is the general-purpose process control system (computer control) used for experimental equipment at ATLAS. During the past year the system was made more reliable by fixing several program bugs, and several new features were implemented. It is now possible to retain a record of how different monitored quantities change as a function of time and to plot this time dependence on a graphics terminal. The graphics package has also been expanded to allow the display of much more detailed information concerning the experimenter's apparatus. It should soon be possible to automatically transfer the information available to SCAMP to the user's DAPHNE event-mode data tape.

G. OTHER RESEARCH

In addition to the above programs, research efforts are included here, generally by staff members involved with research at ATLAS, in other related areas. Extensive calculations have been performed on several aspects of crystalline structure in cooled heavy-ion beams. Nuclear astrophysics experiments have been undertaken to measure the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ cross section, of relevance for the hot-CNO cycle, and the lifetime of the 2.3-keV state in ^{205}Pb , of relevance to the possible use of ^{205}Tl as a solar neutrino detector.

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

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

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

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

By choosing the $^1\text{H}(^{14}\text{N}, ^{14}\text{O})\text{n}\gamma$ reaction and a 175-MeV ^{14}N beam from the ATLAS accelerator, the recoil ^{14}O nuclei from the gamma-ray decay of the $^{14}\text{O}^*(5.17 \text{ MeV})$ state will all be confined within a $\pm 1^\circ$ cone centered at 0° . The major technical difficulty of this measurement is separating the beam (and beam-related products) from the recoil ^{14}O nuclei. Using the split-pole spectrograph, we have successfully identified ^{14}O nuclei at 0° . We expect to reach a sensitivity of $\Gamma_{\gamma}/\Gamma_{\text{T}} \sim 1/6,600,000$, which is far better than the averaged theoretical predictions of $\Gamma_{\gamma}/\Gamma_{\text{T}} \sim 1/22,000$.

*Yale University, New Haven, CT.

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

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

A thin ^{209}Po source on a thin film was used in the experiment; alpha particles were detected with a Si(SB) detector and the electrons with an ionization counter. Preliminary results indicate that the half-life of the 2.3-keV level is either less than 200 ns or greater than 5 μs . Further work is in progress.

c. Measurement of Low-energy Neutrino Absorption Probability in ^{205}Tl (Melvin S. Freedman)

The measurement of the abundant low-energy (p-p fusion) component of the solar neutrino flux by inverse electron capture in ^{205}Tl to an excited state in ^{205}Pb requires an experimental determination of the interaction cross section with about 10% accuracy. The difficult problem of measuring the weak-interaction matrix elements connecting the nuclear states may now be accessible by circulating a beam of completely-stripped $^{205}\text{Tl}^{81+}$ ions in the heavy-ion storage ring now under construction at GSI Darmstadt. The bare ^{205}Tl nuclei can decay only by bound-state β -decay to the $1/2^-$ nuclear excited state of interest in the hydrogenic $^{205}\text{Pb}^{81+}$ ion. The rate of this decay as estimated by three theoretical approaches will give an easily measurable yield of $^{205}\text{Pb}^{81+}$ in an achievable $^{205}\text{Tl}^{81+}$ beam intensity per hour of beam. From this measured rate the neutrino capture cross section is calculable in a straightforward way, but the rate depends critically on the mass difference between the ^{205}Pb and ^{205}Tl ground states. This value

currently ranges from 38-57 keV from various closed-reaction, beta-decay and mass spectrometry measurements, but must be known to within 1 keV to tie down the neutrino cross section. Other measurements are underway and planned to address this need, in association with Professor R. Barber of the University of Winnipeg, using mass spectrometry and at Argonne using L and M X-ray analysis of the decay of ^{205}Pb .

d. Condensed Crystalline States in Confined Ions (J. P. Schiffer and A. Rahman*)

Calculations were started last year using the Energy Research Cray in order to explore the possibility of a condensed state that may be achieved in cooled ion beams contained within storage rings. The spacing between particles in such beams is typically tens of microns. Using the Molecular Dynamics (MD) program developed by Rahman, with periodic boundary conditions to allow the simulation of a continuous beam, the surprising result emerged that the particles arrange themselves in concentric cylindrical shells, and within each shell following a hexagonal close-packed arrangement. At the same time, the overall correlation function showed 14 nearest neighbors, characteristic of a body-centered cubic (bcc) symmetry. The outer shell was very sharply defined, while the inner shells appeared to be somewhat more diffuse; calculations have been limited to 4-shell beams. During the past year this work was slowed down because of the untimely death of A. Rahman.

The calculations have been extended in the past year in several directions¹:

More realistic approximations have been made to real storage rings, including time-dependent focussing, some of the effects associated with circular motion, as well as unequal focussing forces in the horizontal and vertical directions.

The focussing of a beam of particles provides two-dimensional confinement of the ion plasma. Systems of ions have now also been studied in MD calculations with three-dimensional confinement that approximates ion traps, and with one-dimensional confinement.

*University of Minnesota, Minneapolis, MN (deceased).

¹A. Rahman and J. P. Schiffer, Proc. of Workshop and Symposium on the Physics of Stored & Trapped Particles, Stockholm, 14-18 June 1987, to be published.

The one-, two-, and three-dimensional systems of confined, cold, one-component plasmas appear to have the following properties in common.

(i) They all form layered structures, with the outer layer much more sharply defined than the inner ones; nevertheless the layered ordering persists for at least eight shells.

(ii) The particles within one layer, for all systems, form a hexagonal arrangement with equilateral triangles, a symmetry characteristic of two-dimensional Coulomb solids.

(iii) The average correlation between layers is such that for all systems there are 14 nearest neighbors, usually a characteristic of bcc symmetry, that is a feature of infinite three-dimensional Coulomb solids. But bcc symmetry does not have planes with equilateral triangles, the two symmetries are incompatible — and they must therefore be approximate.

(iv) Both the elastic and the frictional forces between layers appear to be unobservably small in the direction of curvature; they are appreciable along the straight directions.

d.1. Time-dependent Focussing in a Beam of Particles (J. P. Schiffer and A. Rahman*)

The early calculations of condensation in cooled ion beams assumed a constant confining force to represent the time-averaged focussing field in a storage ring. In reality, this focussing force is exerted by a series of lenses, and is therefore periodic in nature. Such periodicity has been introduced in the Molecular Dynamics program, and it is found to excite two normal modes in the beam as seen in Fig. I-20. One is a radial oscillation of the beam envelope, and the other a "quadrupole oscillation" in the shape of the beam envelope. The frequencies associated with the two modes differ by a factor of ~ 1.3 and are substantially slower than the likely periodicity in the focussing field. The coupling of these modes to other orthogonal degrees of freedom appears to be small, and thus the heating of the confined particles by the periodic focussing fields does not appear to be appreciable.

*University of Minnesota, Minneapolis, MN (deceased).

Fig. I-20. Results of calculations with periodic focusing forces that are all switched on and off in time (for equal intervalw of 0.5 time units) [left] and with the focusing forces in the two directions on and off out of phase [right]. The top curve shows the average radius of all particles on the left, the average size in the y and z dimensions on the right. The bottom curves show the increase in the (random) kinetic energy component along the axis of the beam: the heat induced by the process. The unit of time is $1/\omega_B$, where ω_B is the betatron frequency. The unit of energy is 10^{-2} of the interparticle Coulomb energy, (q^2/a) . The beam was initially cooled to $r \approx 2000$, the linear beam density is $\lambda = 2.7 (\approx 10^7$ particles in a typical storage ring).

d.2. Shear Induced in a Beam of Particles in a Storage Ring
 (J. P. Schiffer and A. Rahman*)

The cooling of a beam of particles in a storage ring usually implies that all particles are travelling with the same linear velocity. The circular motion inherent in a storage ring necessarily implies that particles travelling side-by-side will have to describe orbits with slightly different circumference -- thus a shear will be introduced with respect to a "cold" beam. The Molecular Dynamics program has been modified to investigate such shear. The elastic modulus of a condensed beam for this type of shear depends on the strength of the focussing forces. For a beam with equal horizontal and vertical focussing the design parameters for rings under construction at present will imply a limiting beam size in a condensed state of a single cylindrical shell as is seen in Fig. I-21. It would seem that a ring with stronger focussing (higher betatron tune) may be necessary for the formation of a multi-layered beam, although several other options need to be explored, such as unequal focussing, or a "cooling profile" that introduces a velocity gradient in the beam consistent with its circular motion.

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Fig. I-21. Various characteristic frequencies determined from MD calculations in units of the betatron frequency, as a function of the linear beam density. The upper hatched strip represents the approximate ring frequency for several storage rings; the lower one that for the proposed Brookhaven RHIC ring. The error bars on the shear frequency represents the accuracy with which these can be estimated from the calculations. The elastic limit against shear would be exceeded when the frequency is below the ring frequency.

d.3. Beams with Unequal Focussing (J. P. Schiffer)

With focussing parameters in the storage ring where the focussing is not the same in the vertical and horizontal directions, the resistance of the beam to shear may perhaps be improved. For the time-independent beam with such asymmetric confinement, the shapes of the shells become elliptical. The eccentricity of the outermost elliptical shell is determined by the ratio of the two (vertical and horizontal) focussing forces. But, since the particles remain approximately equidistant, the eccentricities of the inner shells become increasingly larger, with the innermost shell becoming a single- or double-plane layer for larger asymmetries in the confining forces. The resistance of such a configuration to shear has not yet been investigated systematically as may be seen in Fig. I-22.

Fig. I-22. A beam profile, projected onto a plane perpendicular to the beam, for a MD calculation where the static focusing forces in two directions differed by a factor of two. The linear beam density was 27. Note the increasing eccentricity of the inner shells and the arrangement into parallel sheet, with reasonably well-defined locations, on the innermost layers.

d.4. One-dimensional Confinement (J. P. Schiffer)

As a limiting case for asymmetric focussing, some calculations have been carried out for a plasma of charged particles confined by a harmonic restoring force in only one dimension. The particles spread out in the remaining two dimensions and their density is maintained by the use of periodic repeating cells. The ordering of the particles within each sheet is still hexagonal and the layers have all the characteristics of the beam calculations. The overall correlation function still shows 14 nearest neighbors, yet the hexagonal pattern in the sheets cannot be mapped directly into a bcc symmetry.

d.5. Three-dimensional Confinement (J. P. Schiffer and A. Rahman*)

Calculations with an isotropic, three-dimensional confining force had been carried out earlier, in order to test the influence of periodic boundary conditions. By cooling a system of 2000 particles to lower temperatures (values of the dimensionless parameter Γ of about 5000) spherical shells are formed. The system forms eight shells, with the outermost shell very sharp and the inner shells somewhat wider. As in the cases with one- and two-dimensional (beam) confinement calculations, the particles form a hexagonal pattern on the surface of each spherical shell, and the overall correlation function shows 14 nearest neighbors. This calculated structural configuration may approximate the condition of particles in an ion trap, where laser cooling techniques are being increasingly successful in attaining low temperatures. Such ion traps are being studied at the National Bureau of Standards in Boulder.

*University of Minnesota, Minneapolis, MN (deceased).

d.6. Elastic Constants between Layers (J. P. Schiffer)

The elastic parameters for the interaction between layers has been investigated as is shown in Fig. I-23. For two-dimensional confinement (that simulates a beam) the results were somewhat surprising. There appears to be a restoring force for longitudinal displacement of one shell of particles with respect to the others, and rapid damping of longitudinal motion. But the rotation of one shell about the beam axis appears to proceed smoothly, with very little coupling between the moving shell and the stationary ones. For the three-dimensional case the rotation of one spherical shell also seems to continue unhindered by elastic or damping effects. For one-dimensional confinement the interaction between layers appears to be stronger -- comparable to that for longitudinal motion in the cylindrical case.

Fig. I-23. Components of kinetic energy in various systems are plotted as a function of time, in units of $(1/\omega_{\text{plasma}})$ (where $\omega_{\text{plasma}} \equiv \sqrt{\pi\rho q^2/m}$, the reciprocal of the plasma frequency characteristic for each system). At a given time the particles in one layer (the second from the outside) are given a linear or rotational velocity in a direction perpendicular to the confining force. For the upper two figures the solid line represents translational kinetic energy along the symmetry axis: $(\sqrt{1/2}mv_x^2)$, in units of the dimensionless temperature for $\Gamma = 200$ and the dashed line is the kinetic energy associated with rotation about the axis. On the lower left the solid line is for translational kinetic energy along the imposed motion and the dashed one is for motion perpendicular to the first, both along the planes; for the lower right the dashed line is for rotational and the solid for radial kinetic energy.

d.7. Structure of the Inner Shell (J. P. Schiffer and R. W. Hasse*)

For a limited number of particles that form no more than a single shell, the radial correlation function, the coordination (the average number of particles within a given radius), and various interparticle angles and distances have been studied in more detail. With increasing number of particles per unit length along the beam several changes in configuration may be identified. For very low linear density, the ions arrange themselves in a string along the beam axis. Above a first critical density ($\lambda=0.709$ in dimensionless units) the ions begin to be systematically displaced from the beam axis by their mutual Coulomb repulsion. At first, successive particles tend to be displaced from the axis in opposite directions, that is each successive particle along the beam axis is shifted with respect to the next one by 180° . As the density increases, the particles form a helical arrangement, and the helical structure is replaced by one where the particles are paired, sitting directly opposite each other on a line perpendicular to the beam axis, with the next pair along the axis rotated by 90° . This is followed by another helical arrangement and then again by one with pairs of particles that have the same position along the axis. These changing configurations are being compared with the results obtained by D. Habs at Heidelberg. At a density of about ($\lambda=3.1$) the particles no longer occupy a single shell — some particles appear on the axis in a new row.

*GSI, Darmstadt, W. Germany.

II. OPERATION AND DEVELOPMENT OF ATLAS

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

Fig. II-1. Layout of ATLAS. The system now in use consists of the tandem injecting into the "booster" linac followed by the "ATLAS" linac. The positive-ion injector (now under construction) is shown in the left side of the figure, and the addition to the experimental hall (also under construction) is at the extreme right.

A. OPERATION OF ATLAS

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

The first ion beam was accelerated through a section of the ATLAS linac on June 28, 1978. Since that first proof-of-principle experiment, the size of the linac has been expanded year by year as more accelerating sections became available, and at each step of the way the tandem-linac system has been used regularly for physics research. This operating history is summarized in the top part of Fig. II-2. Note that the accumulated beam time of ATLAS is now more than 30,000 hr., probably greater than the combined beam times of all other superconducting accelerators for ions.

The lower part of Fig. II-2 shows the distribution of projectiles accelerated recently. Ions with masses greater than ^{58}Ni are increasingly in demand by users. Some other operating statistics of ATLAS are given below.

<u>Distribution of Machine Time (hr)</u>	<u>1987</u>	<u>1988*</u>
Research	3611	3700
Tuning	1034	1100
Machine Studies	386	384
Unscheduled maintenance	775	700
Scheduled shutdown	2954	2900
Total (1 yr)	8760	8784

<u>Distribution of Research Time (%)</u>		
ANL Staff	49	48
Universities (USA)	42	43
DOE National Laboratories	2	2
Other Institutions	7	7
Total	100	100

<u>Outside Institutions Represented)</u>		
Universities (USA)	16	17
DOE National Laboratories	2	2
Other	11	11

*Projections based on experience through March 31, 1988

OPERATION of ATLAS SUPERCONDUCTING LINAC

DISTRIBUTION OF BEAM TIME BY MASS APRIL 1, 1986 - MARCH 31, 1987

Fig. II-2. The upper histogram summarizes all running time on the ATLAS superconducting linac. The dip in running time in FY1985 is associated with the completion and commissioning of the present ATLAS system. The lower histogram shows the ion beams accelerated during a recent short period.

During 1987, the accelerator was operated on a regular schedule of 5 1/2 days of running time per week. In addition to this scheduled time, the operation was often extended through the weekend if needed to make up for unscheduled down time during the week. This mode of operation has proved to be quite effective in allowing users to complete planned research and is being continued in 1988 to the extent possible. However, at the present level of funding, it may be necessary to reduce the running time in late 1988.

The operation of ATLAS was interrupted in late 1987 by two periods of scheduled down time required to make technical improvements. One of these periods involved the installation of a third helium refrigerator and the other was needed to carry out major maintenance on the resonators of a cryostat that had not been off line for several years. Both jobs resulted in improved performance of ATLAS.

Looking into the future, ATLAS will be operated in its present form until early 1989, when the Phase I positive-ion injector will be put into operation. The shake down of this new injector will cause some lost time but then, assuming that it operates as planned, the new injector will be used steadily for a period of some six months until another interruption is required for installation of the Phase II injector linac. Thereafter, until late 1990, when the Phase III linac will be ready for service, the tandem and the injector linac will be used alternately, depending on circumstances that cannot be foreseen clearly yet.

B. RECENT IMPROVEMENTS IN ATLAS

ATLAS is a well-developed accelerator that is being used routinely for research. Nevertheless, to the extent that the operating schedule and funding permit, many parts of the accelerator are being steadily improved, as outlined below.

a. Refrigeration Capacity (L. M. Bollinger and J. J. Nixon*)

The long-term problem of a shortage of refrigeration capacity for ATLAS has been ameliorated to some extent by the installation of a third refrigerator. Although the primary function of this device is to cool the Phase I injector linac now under construction, it can also provide about 50 W of cooling for the present linac. This small addition has made it significantly easier to operate ATLAS.

b. Mechanical Failure of Resonators (K. W. Shepard, P. Markovich, and G. P. Zinkann)

Last year we reported that parts of the housing for a number of resonators had cracked because of thermal cycling. These failures have been repaired and the mechanical design has been modified. There have been no further mechanical failures during the past six months, which suggests that the problem has been solved.

c. Spare Cryostat (G. P. Zinkann, C. H. Batson,* and R. Benaroya)

The spare fully-loaded cryostat that has been under construction for the past two years was completed in August 1987 and was immediately put into service as a replacement for an on-line unit that was not working well. This exchange of cryostats was the first step in a systematic program to perfect the performance of the whole linac. The unit that is now off line will be upgraded and then exchanged with an on-line unit later in 1988.

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

As discussed in section E.d., a substantial effort is being made to upgrade the fast-tuner system used to control the phase of the superconducting resonators. One aspect of this is a redesign of the high-voltage pulser used to switch the PIN diodes of each tuner. Six of the improved pulsers have been built and are now in use on-line.

*Engineering Division, ANL.

**Chemistry Division, ANL.

As expected, the performance of the tuners involved has been greatly improved and as a result it has been feasible to operate the associated resonators at field levels that are about 20% higher than had been feasible with the old-model pulsers. Other pulsers of the original design will be gradually replaced over the next few years as time and funding permit.

Considerable effort has also been devoted to a redesign of the voltage-controlled reactance (VCX) part of the fast-tuner system. A prototype unit is now being fabricated and will be tested later in 1988. It is expected that this new VCX will have at least twice the tuning capacity of the units now in use on ATLAS.

e. Phase Stability of Resonators (B. E. Clifft* and J. R. Delayen**)

During the past few years we have become aware that phase settings of one or more resonators of the linac may change for no apparent reason after a long period of stable operation. The main problem generated by this phenomenon is that it destroys an earlier tune of the system, thus requiring a time-consuming repetition of the tune. The effect is not yet understood because of its infrequent and seemingly random character, but all parts of the phase-control system are being examined and parts of the system will be upgraded. This upgrading process is starting with a redesign and replacement of the distribution system for the RF signal from the master oscillator, the unit that controls the phasing of all resonators.

f. North Injector of the Tandem

The high-resolution north injector of the tandem has been gradually perfected during the past year. Now it is always used when it is important to resolve ions with a single mass from the source, as is especially true for accelerator mass spectroscopy. Also, for beams for which the source lifetime is short, the operating efficiency of the system is improved by being able to alternate between the outputs from sources on the east and the north injector.

*Chemistry Division, ANL.

**Engineering Division, ANL.

g. Ion Beams

During the past year users have shown a steadily increasing interest in heavier ions, and hence the upper limit of the ion mass that can be effectively accelerated has been gradually increased with the development and use of Ge, Br, Mo, Ag and I ions. Beams of the Se isotopes are now requested frequently. For routine use, the upper limit is now set principally by the short lifetimes of the foils in the tandem terminal for ions heavier than selenium.

h. Energy-Measurement System (R. C. Pardo, B. E. Clifft,* P. K. DenHartog, D. G. Kovar, W. Kutschera, and K. E. Rehm)

The time-of-flight energy-measurement system has now been fully developed and is used routinely to measure the mean energies of beams from ATLAS. A careful calibration during the past year indicates that the system measures energy with an absolute accuracy of about 5×10^{-4} and a reproducibility of about 2×10^{-4} .

C. LONG-TERM TECHNICAL OBJECTIVES

a. Parasitic Beams (L. M. Bollinger, J. M. Bogaty, P. K. DenHartog, W. Kutschera, and R. C. Pardo)

The uranium upgrade of ATLAS described in section C.c. is expected to provide research capabilities that will be in great demand by users. Also, the kinds of experiments of most interest will require long running time. Because of the immense beam intensities that will be available, the beam could be separated into several parts without causing a shortage of intensity for most experiments. Consequently, in view of the large capital and operating costs involved in the operation and use of ATLAS, we plan to develop systematically a multiple-beam system that will allow the accelerator and the experimental apparatus to be used more effectively.

For the planned multiple-beam system, the basic element is a superconducting beam deflector that can deflect the beam into any two of several beam lines for alternate micro-structure pulses. Several such deflectors and the associated magnets would allow CW beams to be delivered simultaneously to several experimental stations. Our outside users and visitors from other laboratories have shown a keen interest in such a system.

*Chemistry Division, ANL.

Unfortunately, because of the pressure of other activities, it is not feasible to start work on a comprehensive multiple-beam system until 1990. However, as a first step in this direction, during the past year we have developed the capability of switching the ATLAS beam reliably and reproducibly between Areas II and III on a time scale (~ 30 sec) determined by the characteristics of the first magnet at the 40° bend. It is expected that this capability will be used occasionally on a parasitic basis for tests of equipment in one area while the primary user is in the other area. A similar capability is being developed for switching the beam on demand between the five beam lines in Area III. This capability is expected to be quite useful because it will facilitate the preparation of future experiments without much loss of running time for the primary user.

b. Beam Bunching

Excellent beam bunching continues to be important to the users of ATLAS, and consequently this capability is being steadily refined. During the past year the accelerating power of the rebuncher (B_4) for Area III has been increased, which makes it possible to rebunch lighter ions such as ^{16}O more effectively.

A continuing problem is how to measure reliably the widths of tightly-bunched beams (sometimes only 100 ps wide). The method used now is to scatter ions off a gold foil into a silicon detector. A good detector of this kind has adequate time resolution but is easily damaged, and confusion about the quality of a detector has frequently resulted in wasted effort being devoted to unnecessary beam tuning. A new kind of channel-plate-based timing detector that is expected to eliminate this problem is being developed and will be tested on line later in 1988.

c. General Upgrade of ATLAS-Linac Technology

We plan to undertake a general upgrading of various subsystems of the present ATLAS linac. This long-term project, which was started on a small scale in 1987, must continue at a modest level in FY 1988 and FY 1989 because of a shortage of funds. However, the budget request for FY 1990 includes funds that will allow the most urgent parts of the technology upgrading to proceed more rapidly.

Much of the technology now used in the ATLAS linac was developed during the mid 1970's. Although this technology has provided good service over the past decade, now much of it could and should be improved in ways that would result in better performance and especially in more reliable operation of the accelerator system. The subsystems for which upgrading is most clearly needed include the fast tuner system and the RF pulse and amplitude control system, both of which impact on the operational reliability of the linac to a major extent. Also, inadequate helium refrigeration capacity is a continuing long-term problem, and there is need for a good spare resonator (now there are none).

Some of the technology-upgrading needs mentioned above are being taken care of gradually over a long period of time with our normal annual complement of Capital Equipment funds. An example is the fabrication during the past year of six of the 46 PIN-diode pulsers needed to upgrade the fast-tuner system (see section B.d.). This gradual approach is satisfactory for the development and testing of prototype units, but is an unreasonably slow way to upgrade the system as a whole.

The proposed upgrading is expected to increase substantially the performance and the operating reliability of ATLAS. In particular,

- i the improved fast-tuner system is expected to increase accelerating fields by about 20%,
- ii the improved phase and amplitude control units may eliminate the phase-instability problem discussed in section I.B.e.,
- iii a spare resonator will reduce turn-around time for some major maintenance tasks,
- iv installation of an additional refrigerator will increase operational flexibility and the ability to operate at high accelerating fields,
- v the VCX cooling control will reduce the cost for liquid nitrogen by about \$20,000 annually, and
- vi all of the proposed items will contribute to a general improvement in reliability.

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

The continuing strong interest in ATLAS (outside users were involved in 70% of all experiments performed in 1987) makes it clear that the user-assistance program fills an essential function.

The outside user involvement increased by about 10% over that in 1986. 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 instruction in the use of and technical information about ATLAS and its experimental systems to users; (3) to assist outside users in all aspects of initiating and planning an experiment; (4) to the extent that is appropriate and feasible, to assist users in the actual performance of experiments; (5) to provide instruction and help with the use of computer hardware and software; (6) to instruct the users in the safety procedures to be followed when using the ATLAS facility; (7) to assist in the operation of the technical support group; and (8) provide an interface between the user and the technical support and ATLAS operation groups.

The Program Advisory Committee (PAC) for ATLAS (having five members from other institutions and two from Argonne) continues to meet regularly during the year. PAC meetings were held on 6 June and 6 November, 1987 to recommend experiments for running time at ATLAS. The present PAC members are Birger Back (ANL), David Balamuth (University of Pennsylvania), Douglas Cline (University of Rochester), C. Lewis Cocke (Kansas State University), Teng Lek Khoo (ANL), Luciano Moretto (Lawrence Berkeley Laboratory), and Peter Parker (Yale University). On the average, the PAC is asked to review 30 proposals for 130 days of running time per meeting. The time requested at the 6 June meeting was extraordinarily large consisting of 39 proposals for 159 days. The running time requested in these proposals continues to stay at the level of approximately twice the number of days available for experiments.

The PAC meeting on 6 November was preceded on 5 November by an "open PAC" meeting that was attended by about 45 scientists. The Open PAC meeting was held to give the PAC members a better understanding of the ongoing programs at ATLAS for both the outside and inside users. The Uranium Upgrade and plans to

extend the experimental facilities at ATLAS were also discussed. The speakers at this year's meeting were L. Bollinger (ANL), J. Kolata (University Notre Dame), R. V. F. Janssens (ANL), R. R. Betts (ANL), F. Wolfs (ANL), S. Sanders (ANL), B. Wilkins (ANL), W. Trzaska (Purdue University), W. Kutschera (ANL), J. LaVerne (University of Notre Dame), P. DeYoung (Hope College), A. E. Livingston (University of Notre Dame), and W. Phillips (University of Manchester).

The members of the ATLAS User Executive Committee are James Kolata (University of Notre Dame), Chairman, Charles Maguire (Vanderbilt University), Udo Schroeder (University of Rochester), and Thomas Cormier (University of Rochester).

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 1987 are listed below. The spokesperson for each experiment is given in square brackets after the title. The names in parentheses are Argonne collaborators.

- (1) Study of the High-spin Structure of ^{219}Ac [Drigert]
M. Drigert, EG&G Idaho; K. Beard, University of Notre Dame;
J. Cizewski, Rutgers University; (A. Ahmad, B. Dichter,
R.V.F. Janssens, W.-C. Ma)
- (2) Lifetime Measurements and Nuclear Structure Above $I=44$ in ^{154}Dy [Ma]
M. Drigert, EG&G Idaho; (W.-C. Ma, A. Ahmad, B. Dichter, R. Holzmann,
R.V.F. Janssens, T.L. Khoo, T. Wang)
- (3) Measurement of Atomic Transition Wavelengths in Ni^{26+} (550 MeV)
[Livingston]
A.E. Livingston, A. Zacarias, Y. Lu, University of Notre Dame;
(H. Berry, R. Dunford)
- (4) Lifetime Measurements in $^{189,191}\text{Tl}$ [Garg]
U. Garg, K. Beard, L. Goettig, A. Morsad, University of Notre Dame;
M. Drigert, EG&G Idaho; (R.V.F. Janssens, W.-C. Ma, R. Holzmann,
T. L. Khoo)

- (5) Radiation Chemistry Studies with Heavy Ions (^{16}O) [LaVerne]
J. LaVerne, R. Schuler, R. Steinback, University of Notre Dame
- (6) Test of New NaI Light-ion Detectors [Davids]
F. Prosser, V. Reinert, University of Kansas; C. Maguire, Vanderbilt University; (C. Davids, D. Kovar)
- (7) Study of the Tilting-Mode Relaxation in the HI-induced Reaction $^{165}\text{Ho} + ^{58}\text{Ni}$ at 7.0 and 10.0 MeV per Nucleon [Töke]
J. Töke, J. Wile, I. Govil, University of Rochester; (K.E. Rehm)
- (8) Radiation Chemistry Studies with Heavy Ions (^{58}Ni) [LaVerne]
J. LaVerne, R. Schuler, R. Steinback, University of Notre Dame
- (9) Measurement of Atomic Transition Wavelengths in Ni^{26+} (350 MeV) [Livingston]
A. E. Livingston, A. Zacarias, University of Notre Dame; (H. Berry, R. Dunford)
- (10) Precision X-ray Wavelength Measurements in H-like and He-like Ions [Deslattes]
R. Deslattes, National Bureau of Standards; (R. Dunford, R. Pardo)
- (11) Entrance Channel Dependence in the Population of a Superdeformed Band in ^{152}Dy [Khoo]
U. Garg, University of Notre Dame; M. Drigert, EG&G Idaho; P. Daly, M. Quader, W. Trzaska, Purdue University; (T.L. Khoo, R. Holzmann, W.-C. Ma, R.V.F. Janssens)
- (12) Production of ^{272}X in the Reaction $^{34}\text{S} + ^{238}\text{U}$ [Henning]
W. Henning, GSI, (B. Back, B. Glagola, J. Keller, W. Kutschera, K.E. Rehm)
- (13) Fission of Nuclei with $A \approx 80$ [Betts]
A. Smith, P. Evans, University of Oxford; (R.R. Betts, S. Sanders, F. Videbaek, D. Henderson, B. Back, B. Wilkins)
- (14) Lifetime Measurements and Nuclear Structure Above $I=44$ in ^{154}Dy [Ma]
P. Daly, Z. Grabowski, M. Quader, W. Trzaska, Purdue University; U. Garg, University of Notre Dame; M. Drigert, EG&G Idaho; (W.-C. Ma, A. Ahmad, B. Dichter, T.L. Khoo, R. Holzmann, R.V.F. Janssens, T. Wang)
- (15) High-spin States in ^{149}Ho , ^{149}Er and ^{150}Er with Compton-suppressed Spectrometers [Daly]
P. Daly, Z. Grabowski, M. Quader, Purdue University; M. Drigert, EG&G Idaho; (R. Holzmann, T.L. Khoo, W.-C. Ma, R.V.F. Janssens)

- (16) Measurement of the Half-life of ^{126}Sn ($\sim 10^5$ yr) by Accelerator Mass Spectrometry [Kutschera]
M. Paul, Hebrew University; M. Kaba, Abidjan University, Ivory Coast, Africa; B. Schneck, Technical University, Munich; (W. Kutschera, A. Ahmad, P. Billquist, B. Glagola, R. Pardo, K.E. Rehm, J. Yntema)
- (17) Measurement of the Gamma-ray Width of the 5.17-MeV State in ^{14}O [Wang]
P. Parker, P. Magnes, Yale University; (T. Wang, R. Holzmann, K.E. Rehm, W.-C. Ma, S. Sanders)
- (18) Study of Triaxiality in the Nucleus $^{221}_{91}\text{Pa}$ [Ahmad]
M. Drigert, EG&G Idaho; (I. Ahmad, R.V.F. Janssens, T.L. Khoo, R. Holzmann, W.-C. Ma, B. Dichter)
- (19) Incomplete Fusion Reactions Induced by ^{12}C at 10-15 MeV/u [Tserruya]
I. Tserruya, Weizmann Institute; M. Vineyard, J. Bauer, University of Richmond; F. Prosser, University of Kansas; (D. Kovar, B. Glagola, B. Wilkins, D. Henderson)
- (20) On-Line Testing of the Superconducting Electron Spectrometer [Trzaska]
W. Trzaska, Z. Grabowski, Purdue University; J. Cizewski, Rutgers University; (R.V.F. Janssens, W.-C. Ma)
- (21) Space-time Extent of the Reaction Complex and Related Aspects of the Reaction $^{16}\text{O}+^{27}\text{Al}$ [DeYoung]
P. DeYoung, D. Kortering, T. Koppenol, C. Gelderloos, Hope College; J. Alexander, G. Auger, S. Kox; SUNY Stony Brook; G. Gilfoyle, University of Richmond; (D. Kovar, D. Henderson)
- (22) Electromagnetic Transitions in Neutron-rich Nuclei in the A=40 Region via Reactions of ^{36}S with ^7Li [Kozub]
R. Kozub, R. Moyers, R. Bybee, Tennessee Technological University; J. Kolata, U. Garg, University of Notre Dame; M. Drigert, EG&G Idaho; (R.V.F. Janssens, T.L. Khoo, R. Holzmann)
- (23) Temperatures and Level Densities of Highly-Excited Nuclei [Natowitz]
J. Natowitz, R. Schmitt, R. Wada, K. Hagel, Y. Lou, L. Cooke, H. Utsonomiya, Texas A&M University; G. Nebbia, G. Viesti, G. Prete, G. Nardelli, R. Zanon, B. Fornel, Laboratori Nazionali di Legnaro; P. Gonthier, Hope College; (B. Wilkins)
- (24) Energy Dissipation and Mass Flow in the $^{58}\text{Ni}+^{208}\text{Pb}$ Reaction [Lee]
S. Lee, M. Ogihara, T. Nakagawa, University Tsukuba; H. Koerner, Technical University Munich; (B. Back, J. Keller, B. Glagola, B. Wilkins, D. Henderson, S. Sanders)
- (25) Measurement of the Half-life of ^{126}Sn ($\sim 10^5$ yr) by Accelerator Mass Spectrometry (^{109}Ag tune)[Kutschera]
M. Paul, Hebrew University; (W. Kutschera, I. Ahmad, P. Billquist, B. Glagola, R. Pardo, K.E. Rehm, J. Yntema)

- (26) Fission of $^{40}\text{Ca} \rightarrow ^{12}\text{C} + ^{28}\text{Si}$ Following Inelastic Scattering [Fulton]
B. Fulton, S. Bennett, University of Birmingham; S. Allcock, A. Smith,
University of Oxford; (R.R. Betts, S. Sanders, B. Back, F. Videbaek)
 - (27) Lifetime of the 2^1S_0 State of Helium-like Ni^{26+} [Dunford]
A.E. Livingston, University of Notre Dame; M. Hass, Weizmann
Institute; K.-O. Gröeneveld, J.W. Goethe Universität; L. Curtis,
University of Toledo; (R. Dunford, H.G. Berry)
 - (28) Target Residues of the Interaction of Copper with ^{12}C Ions [Porile]
N. Porile, S. Cho, Purdue University
 - (29) Inner-shell Electron Properties of ^{57}Fe [Phillips]
W. Phillips, University of Manchester; W. Henning, GSI; (J. Schiffer,
K.E. Rehm, W. Kutschera, B. Glagola, I. Ahmad, T. Wang)
 - (30) Conversion-coefficient Determinations in ^{149}Ho and ^{150}Ho [Trzaska]
W. Trzaska, Z. Grabowski, Purdue University; M. Drigert, EG&G Idaho;
(R.V.F. Janssens, A. Ahmad, W.-C. Ma)
 - (31) Determination of the Transition Multipolarities in ^{219}Ac and ^{218}Ra
[Drigert]
M. Drigert, EG&G Idaho; J. Cizewski, Rutgers University; W. Trzaska,
Z. Grabowski, M. Quader, Purdue University; (R.V.F. Janssens,
W.-C. Ma)
 - (32) Search for Superdeformed States in ^{149}Gd [Janssens]
M. Hass, Weizmann Institute; M. Drigert, EG&G Idaho; K. Beard,
University of Notre Dame; G.E. Rathke, GSI; (R.V.F. Janssens,
T.L. Khoo, W.-C. Ma, I. Ahmad)
 - (33) Population Mechanism of Superdeformed Bands [Khoo]
W. Trzaska, M. Quader, Purdue University; U. Garg, K. Beard,
University of Notre Dame; M. Drigert, EG&G Idaho; G.E. Rathke, GSI;
(T.L. Khoo, R.V.F. Janssens, I. Ahmad, F. Wolfs, W.-C. Ma)
- B. Outside Users of ATLAS and of ATLAS Technology During the Period
January 1, 1987 - December 31, 1987
- (1) University of Notre Dame
 - J. J. Kolata
 - U. Garg
 - A. Morsad
 - L. Goettig
 - K. Beard
 - P. Wilt
 - A. E. Livingston
 - A. Zacarias
 - Y. Lu
 - J. A. LaVerne
 - R. H. Schuler
 - R. T. Steinback

- (2) Purdue University
 - P. J. Daly
 - Z. W. Grabowski
 - M. Quader
 - W. H. Trzaska
 - N. Porile
 - S. Cho
- (3) SUNY, Stony Brook
 - J. Alexander
 - S. Kox
 - G. Auger
- (4) University of Kansas
 - F. W. Prosser
 - V. Reinert
- (5) Texas A&M University
 - J. Natowitz
 - R. Schmitt
 - R. Wada
 - K. Hagel
 - Y. Lou
 - L. Cooke
 - H. Utsonomiya
- (6) Hope College
 - P. DeYoung
 - P. Gonthier
 - D. Kortering
 - T. Koppenol
 - C. Gelderloos
- (7) University of Toledo
 - L. Curtis
- (8) Laboratori Nazionali di Legnaro
 - G. Nebbia
 - G. Viesti
 - G. Prete
 - B. Fornal
 - R. Zanon
 - G. Nardelli
- (9) EG&G Idaho
 - M. Drigert
- (10) Hebrew University
 - M. Paul

- (11) Tennessee Technical University
 - R. Kozub
 - M. Hindi
 - R. Moyers
 - R. Bybee
- (12) University of Manchester
 - W. Phillips
- (13) Rutgers University
 - J. Cizewski
- (14) Vanderbilt University
 - C. F. Maguire
- (15) Weizmann Institute
 - I. Tserruya
 - M. Hass
- (16) National Bureau of Standards
 - R. Deslattes
- (17) GSI
 - W. Henning
 - G. E. Rathke
- (18) University of Rochester
 - J. Töke
 - U. Schroeder
 - I. Govil
 - J. Wile
- (19) University of Birmingham
 - B. Fulton
 - S. Bennett
- (20) University of Oxford
 - A. Smith
 - P. Evans
 - S. Allcock
- (21) Yale University
 - P. Parker
 - P. Magnes
- (22) University of Richmond
 - M. Vineyard
 - J. Bauer
 - G. Gilfoyle
- (23) J.W. Goethe Universität
 - K.-O. Gröeneveld

(24) Technical University of Munich

H. Koerner
B. Schneck

(25) University of Tsukuba

S. Lee
M. Ogihara
T. Nakagawa

(26) Abidjan University

M. Kaba

(27) Florida State University

J. Fox
A. Frawley
E. Myers

(28) Kansas State University

T. Gray
K. Karnes
V. Needham

C. Summaries of the continuing User Programs, January 1, 1987 to December 31, 1987

C.a. The University of Notre Dame

C.a.1. Nuclear Physics (U. Garg, M. Drigert*, K. Beard, L. Goettigt, J. Kolata, J. Hinnefeld‡, and R. Vojtech)

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 Pt-Os-Ir-Tl region, with emphasis on the origins of the backbending phenomenon in these nuclei, measurements of the lifetimes of high-spin yrast states, and investigation of shape coexistence. This group has also participated in most of the experiments performed with the new BGO gamma-ray facility. Dr. M. Drigert was based at Argonne for a full year beginning in the summer of 1986 in order to render the collaboration more effective. Another project concerns the study of incomplete fusion, quasielastic reactions and the emission of light particles. In the past year one study of the $^{28}\text{Si}+^{208}\text{Pb}$ system was undertaken. It is planned to extend this study to

*Now at EG&G Idaho, Inc., Idaho Falls

†Visitor from Poland

‡Now at KVI Groningen, The Netherlands

higher energies in the future. A major activity of this past year was the continuation of the second phase in the construction of a 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. This construction project is nearing completion and the first experiments with the full complement of detectors are already in progress.

C.a.2 Atomic Physics (A. E. Livingston, A. D. Zacarias, Y. N. Lu)

In a collaboration with the Atomic Physics group of Argonne, measurements are being made of the fine structure in lithium-like and helium-like ions using beam-foil spectroscopy. The recent effort has been devoted to extending the measurements of the $2s-2p$ ($J=2$) transition in helium-like titanium to helium-like nickel and bromine ions. Precise measurements of $2s-2p$ transition energies in simple (few-electron) atomic systems provide stringent tests of several classes of current atomic-structure calculations. In the past year measurement of the $1s2s^3s_1 - 1s2p^3p_2$ transition energy in helium-like nickel ($^{58}\text{Ni}^{26+}$) has been completed. A preliminary analysis yields a value of 226.21 ± 0.06 Å in agreement with the theoretical value of 226.21 ± 0.04 Å. This is the most precise measurement of a high- Z $2s-2p$ transition energy. The group is also participating in a measurement of the lifetimes of the 2^1S_0 state in helium-like nickel. This state is forbidden to decay to the ground state by emission of two E1 photons. The decay radiation forms a continuum out to the transition energy of about 8 keV. The radiation is detected with a Si(Li) detector. The excited state is formed in a thin carbon foil which is moved relative to the detector by means of a precision translator. The decay rate is measured as a function of foil-detector distance to determine the lifetime. The first run of this experiment was completed in the past year.

C.a.3 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 ^{16}O and ^{58}Ni projectiles at ATLAS energies. In the next year, these experiments will be extended to the full ATLAS energy for ^{11}B and a new set of experiments using a Fricke dosimeter.

C.b. Purdue University (P. Daly, Z. Grabowski, M. Quader, and W. Trzaska)

The Purdue University group is working on high-spin nuclear states at ATLAS, with several thesis students. They use in-beam gamma-ray techniques directed at several aspects of nuclear structure at high spin, testing the validity of the $Z=64$ sub-shell closure through spectroscopic studies of $N=82$ nuclei close to the proton drip line. They have extended these studies in the last year by making use of the Compton-suppressed germanium detectors of the BGO facility. The group has also built a superconducting solenoid lens that is used as a conversion-electron spectrometer. The solenoid was installed at ATLAS in target area II this past year and the first tests were performed in July. Since that time, two successful experiments have been run with the device.

C.c. Tennessee Technical University (R.L. Kozub, J.F. Schriner, M.M. Hindi, R. Moyers, and R. Bybee)

The group from Tennessee Technical University is interested in the structure of neutron-rich nuclei in the $A=40$ region. These are studied at ATLAS using inverse reactions (such as $^{36}\text{S}+^9\text{Be}$ and $^{36}\text{S}+^6\text{Li}$) in experiments where gamma rays measured with the Argonne-Notre Dame BGO gamma-ray facility are detected in coincidence with charged particles (p , d , ^3He , ^4He). In order to perform these experiments they have built a small chamber holding two $\Delta E-E$ telescopes which, nevertheless, fits inside the space available in the BGO array. This chamber has proven to be very useful for several other experiments performed at the Laboratory. Measurements using neutron- γ coincidence techniques are also being discussed, with the TTU group playing a major role in construction of the detectors.

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

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

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

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

C.f. University of Toledo (L. Curtis, and R. Schectman)

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

C.g. Western Michigan University and Lawrence Berkeley Laboratory
Collaboration (J. Tanis, M. Clark, W. Graham, E. Bernstein, and
 K. Berkner)

This group has begun a series of atomic-physics studies at ATLAS to measure coincidences between x-rays and the outgoing projectile charge states in ion-atom collisions. The goal of this work is to probe fundamental atomic interactions in ion-atom collisions by correlating projectile charge-state changing events with x-ray emission. In the experiment, a range of energies was used to span the region of resonant transfer and excitation for high-energy Li-like nickel ions. This process is a close analog of dielectronic recombination which is of fundamental interest in plasma physics. The experiments carried out at ATLAS with fast Ni beams represent the heaviest system studied to date. There have been two runs of this experiment. The first run, which took place in January 1986, was set up in the large scattering chamber and involved electrostatic analysis of the charge states emerging from the target. In the second run, which took place in October 1986, the magnetic spectrograph in Target Area III was used. Additional runs of the experiment will be required to complete the data for Ni.

D. ATLAS - Technology Transfer

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

D.a. Florida State University (J. Fox, A. Frawley, and E. Myers)

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

D.b. Kansas State University (T. Gray, K. Karnes, and V. Needham)

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

E. THE POSITIVE-ION INJECTOR

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

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

Our new project, aimed at replacing the present negative-ion source and tandem injector of ATLAS with a positive-ion source and superconducting-linac injector, is also expected to have a significant impact on the development of accelerator technology.

a. Plans for the Positive-Ion Injector

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

The positive-ion source for the new system is an electron-cyclotron-resonance (ECR) source on a 350-kV voltage platform. Both mass analysis and a first stage of bunching will be carried out on the voltage platform. A second-stage buncher will be added in front of the linac, at ground potential. The source, first tested in October 1987, is the first ECR source operated at high potential.

The injector linac being built to accelerate the low-velocity ions from the ECR source will consist of an array of four different kinds of independently-phased superconducting structures, all having 4 accelerating gaps formed by 3 drift tubes. These four classes of units are sized to be optimum for projectiles with relative velocities β of 0.009, 0.015, 0.025, and 0.037.

The first three of these types operate at 48.5 MHz and the last type operates at $3/2 \times 48.5 = 72.75$ MHz. In total, the injector linac will have 18 resonators.

*Engineering Division, ANL.

**Chemistry Division, ANL.

Construction of the positive-ion injector is being carried out in three phases. In Phase I, the goal is to build a small but useful prototype system consisting of a 3-MV linac and the ECR source on its voltage platform. The linac will have just 5 resonators, all but one of which are being built as prototype units. The overall length of the linac will be only 10 ft. Because of the high charge state of ions from the ECR source, even this tiny system will be superior to the present FN-model tandem as an injector for ions with $A > 40$ and will be vastly superior for two classes of ions: (a) those (such as calcium) that are difficult to make with a negative-ion source and (b) those with $A > 80$. Phase I will be completed in late 1988 or early 1989.

Because of its limited accelerating power, the Phase I linac will be useful only for ions with $A < 130$. In Phase II, the addition of seven more resonators will extend the upper mass limit to at least $A = 190$ and possibly to lead ions. The availability of energetic ions in the upper half of the periodic table will greatly strengthen most of the experimental program by making it feasible to use inverse reactions (heavy projectiles on light targets).

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

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

Work on the positive-ion injector is proceeding on a broad front, including refinement of the ECR source and its voltage platform, resonator fabrication and testing, cryostat design and fabrication, improvements in phase-control technology, fabrication of electronic control circuits, design of bunching, beam-line and linac-control systems, and building modifications. Additional information about some of these topics is outlined below.

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

The electron-cyclotron-resonance (ECR) ion source and its voltage platform have been completed in all essentials, and on October 21, 1987 the source was operated for the first time. Since then, various technical problems have been solved and performance of the source has been steadily improved. In general terms, the source and its voltage platform operate successfully, although many refinements are still needed, of course.

1. ECR Ion Source

The main design features of the ECR source were described in last year's report and will not be repeated here except that the RF system is designed to provide 2.5 kW of power at 10.25 GHz. Our goal was to build a source that can operate on a voltage platform and still compare favorably with existing general-purpose ECR sources with respect to charge-state distribution and beam current. The results obtained to date indicate that this primary objective will be met.

In the course of bringing the ECR source into operation, numerous technical problems have been encountered and solved, in some cases by the redesign of parts of the apparatus. These difficulties include the failure of several components in the RF power system, voltage breakdown in the extraction system, and failure of a pump in the vacuum system. One satisfying success has been that the first stage of the source, which caused trouble initially in most other sources, worked well from the beginning in our source.

An important requirement for our ECR is that it must be able to provide intense high-charge-state beams for nearly all ions, especially materials that are normally solids. Consequently, the plasma chamber has been provided with unusually convenient access. Now that the basic ECR source is functioning well for light gaseous material, a major task for the remainder of 1988 will be to develop techniques for using solid feed materials, especially for elements in the upper part of the periodic table.

While the ECR source is still in a developmental stage it is being used on a part-time basis for atomic-physics experiments. This usage is proving to be very beneficial since it provides realistic long-term burn-in tests for both the source and the voltage platform.

ii. High-Voltage Platform

The high-voltage platform on which the ECR sources is located is designed to operate at 350 kV above ground potential. Power is transmitted up to the platform by means of an isolation transformer, and the resulting heat (up to 50 kW) is removed by means of low-conductivity flowing water.

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

The only serious problem encountered with the voltage platform is that the isolation transformer has broken down twice. The rebuilt transformer will soon be put into service again.

c. Superconducting Accelerating Structures for Low-Velocity Ions (K. W. Shepard, C. H. Batson,* P. Markovich, and G. P. Zinkann)

Three of the four types of new resonators required for the injector linac have been completed and fully tested, and fabrication of the fourth type is nearing completion. All three of the tested units operate at accelerating fields well above our original assumptions.

*Engineering Division, ANL.

i. The 48.5-MHz Resonators for $\beta = 0.009$ and $\beta = 0.015$

As reported last year, the prototypes for these two types of structures have been completed, fully tested, and are ready for on-line use. Fabrications of a second $\beta = 0.015$ resonator for the Phase II linac is underway.

ii. The 48.5 MHz, $\beta = 0.025$ Resonator

Fabrication of the prototype $\beta = 0.025$ unit has been completed and it has been successfully tested. The 10-inch length of this structure along the beam direction is large enough that it is feasible to use fabrication techniques that are similar to those used on the split-ring resonators. This similarity is reducing fabrication costs to a significant extent.

The performance of the $\beta = 0.025$ prototype is considerably better than had been assumed, although not to the extent that was achieved for the $\beta = 0.009$ type. For the $\beta = 0.025$ unit the maximum accelerating field was 6.5 MV/m for stable CW operation and was 4.5 MV/m for an RF-power loss of 4W, whereas we have assumed that it would be used on line at 3.0 MV/m.

Fabrication of the second $\beta = 0.025$ unit required for Phase I is well advanced, and several units for Phase II have been started. The drift-tube assembly driven by the 1/4-wave line of a $\beta = 0.025$ resonator is pictured in Fig. II-3.

iii. The 72.75-MHz, $\beta = 0.037$ Resonator

This unit has the same 10-inch active length and the drift-tube structure as the $\beta = 0.025$ unit; the higher RF frequency is achieved by using a shorter inductive line. The similarity between the two types reduces costs greatly.

Fabrication of the $\beta = 0.037$ unit is progressing smoothly, and the unit is expected to be ready for testing in April 1988. This testing, if successful, will complete the development of resonators for the injector linac.

Fig. II-3. Drift-tube assembly driven by the 1/4-wave line of the $\beta = 0.025$ resonator and also the $\beta = 0.037$ resonator.

d. Other Injector Technology

- i. Improved Fast Tuner (K. W. Shepard, C. H. Batson*, J. M. Bogaty, B. E. Clifft**, and G. P. Zinkann)

The fast tuner for each resonator of ATLAS is a voltage-controlled reactance (VCX) that consists of a parallel-plate capacity that can be shorted by a parallel set of 10 PIN diodes that are switched on and off with a duty cycle controlled by a phase-error signal. The original version of this tuner, developed in the 1970's, has operated well but it does not have as much tuning capacity or as long a lifetime as is desirable. A continuing effort to upgrade the performance substantially is now well advanced.

An improved version of the high-current high-voltage pulser required to switch the PIN diodes has been thoroughly tested, and six of the new pulsers have been used in on-line operation for several months. The good results obtained indicate that the new pulser is satisfactory for use in the injector linac.

Development of the VCX of the fast tuner system is still in progress, but several prototypes have given good results. An ATLAS-type split-ring resonator controlled by one of the new fast tuners was able to operate stably at 6 MV/m, whereas the same resonator with a fast tuner of the original design limited at about 3.5 MV/m. This remarkable improvement indicates that we are close to having a very good tuner for the injector linac and that it is possible to increase substantially the performance of the resonators in the existing ATLAS linac.

*Engineering Division, ANL.

**Chemistry Division, ANL.

- ii. Beam-Line Cryostat (K. W. Shepard and P. Markovich)

Two beam-line cryostats are now being fabricated, one for the Phase I linac and a second for the Phase II linac. The vacuum chamber of the Phase I cryostat was completed in March 1988, and the assembly of internal components started immediately.

The main challenge of the cryostat design is the large size required to house the low- β resonators, which have very long inductive elements. In the final design, the cryostats are top-loading rectangular boxes that are about 8 ft. high, 3 ft. wide, and 11 ft. long. The resonators in the cryostat will be cooled by way of pool boiling.

iii. Electronics and Beam Line (B. E. Clifft,* P. K. DenHartog,
J. M. Bogaty, F. H. Munson, Jr., and R. C. Pardo)

The RF, cryogenic, and vacuum control systems for the injector linac are closely similar to those of the present accelerator. Most of the component circuits for these systems for the Phase I injector are now being fabricated.

The beam line linking the ECR source to the injector is now being designed. This line will incorporate mass (q/A) analysis, beam bunching, beam chopping, and diagnostics. Since the energy of the heavy ions incident on the injector is so low, it is believed that all diagnosis of longitudinal phase space must be done in terms of ion flight time. Design studies of special detectors for this purpose are underway.

iv. Cryogenic System (L. M. Bollinger and J. M. Nixon**)

The injector linac will be cooled by means of flowing liquid helium that maintains liquid helium in a manifold in each cryostat, and liquid from these manifolds reaches the resonators by gravity flow. The source of helium is a refrigerator that can either be dedicated to cooling the injector or can be linked to the two existing refrigerators that cool ATLAS.

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

*Chemistry Division, ANL.

**Engineering Division, ANL.

F. BASIC TECHNOLOGY OF RF SUPERCONDUCTIVITY

- a. RF Properties of an Oxide-Superconductor Half-Wave Line
(J. R. Delayen,* K. C. Gorreta,** R. B. Poeppel,** and K. W. Shepard)

Cylindrical rods of $\text{YBa}_2\text{Cu}_3\text{O}_{7-8}$ from 0.6 to 1.9 mm in diameter and up to 565 mm long have been used as the center conductor of a half-wave resonant coaxial line. The resonant line can be immersed in liquid nitrogen, which provides excellent cooling of the current-carrying superconducting surface, even in the presence of substantial rf losses. Such superconducting resonant lines have been operated at frequencies of a few hundred MHz and at rf surface magnetic fields up to 150 G at 77 K.

This experiment demonstrates a macroscopic (34 cm^2 of superconducting surface) RF device with RF losses substantially less than can be obtained with any normal conducting material for temperatures less than 77 K and magnetic fields less than 1 G.

- b. Superconducting RF Cavity in a DC Magnetic Field (R. Benaroya and K. W. Shepard)

A superconducting RF cavity has been operated in the presence of an external magnetic field up to 2.4 kG. Measurements on the 48.5 MHz cavity were performed at 4.2 K. The external field was produced by an unshielded 60-kG superconducting solenoid 5.8 cm from the cavity. No degradation of cavity Q was observed for fields on the outer surface of the cavity up to 1240 gauss. This result is consistent with no flux penetration of the cavity surface for fields up to the first critical field of niobium at 4.2 K, and shows that strong focussing elements with large fringing magnetic fields may be placed immediately next to Nb superconducting accelerating structures without causing performance degradation.

*Engineering Division, ANL.

**Materials and Components Technology Division, ANL.

III. MEDIUM-ENERGY NUCLEAR PHYSICS AND WEAK INTERACTIONS

In order to explore the internal structure of the nucleon and particularly those aspects which play a role in shaping the character of nuclear forces, the medium-energy research program in the Argonne Physics Division emphasizes studies of excitations of the nucleon in nuclear matter, their modes of propagation and decay. Specific research topics in this area include pion propagation, delta resonance formation, and quark degrees of freedom in the nuclear medium. Because energetic leptons provide an accurate well-understood probe of these processes, increasing emphasis has been placed on experiments involving electron-scattering and deep-inelastic muon scattering. High priority has been given to an experiment (E665) in which Argonne members are collaborating, performed at Fermilab with 500-GeV muons. Deep-inelastic muon scattering will be observed in coincidence with leading hadrons from a variety of nuclei. The very high muon energy and more detailed particle identification distinguish this measurement from previous experiments. The primary objectives of the collaboration are a study of the quark hadronization process and the mass-dependence of the quark structure functions. The data from this experiment will address a central issue in nuclear physics, the modification of the structure of the nucleon in nuclear matter. The Argonne group has assumed the primary responsibility for coordination of the software development for data acquisition and for the refitting, testing, and operation of one of the gas Cerenkov particle-identification detector systems.

The Argonne group provides the leadership for two experiments using high-energy electrons which are in progress at the SLAC NPAS facility. One concerns excitation of the delta, an essential element of the force between nucleons at short distances. The experiment will provide the first separation of longitudinal and transverse electromagnetic excitations in the delta region in nuclei. While the transverse component of the cross section is essential for a detailed study of the delta, the longitudinal cross section measurements will provide information on the Coulomb sum rule, an important issue in understanding nucleon properties in the nuclear medium. The second experiment concerns the measurement of the deuteron photodisintegration cross section above 1.0 GeV. The data from this measurement will be of great interest because they will provide a direct test of the divergent predictions of the perturbative QCD and Boson-exchange models of the nucleon-nucleon force. To prepare for these measurements the Argonne group has developed, installed, and modified the detection instrumentation of the SLAC 1.6-GeV spectrometer.

A substantial portion of the technical resources of the medium-energy physics program are devoted to the development of a new target technology which would be used to study elastic electron-deuteron scattering to very high momentum transfer. The tensor polarization of the recoil deuteron in this kinematic region is very sensitive to non-nucleonic effects in nuclei, most notably meson-exchange and quark effects. To perform such measurements, the Argonne group has proposed that a polarized deuterium gas target be installed in an electron storage ring and that the interactions of the gas target with the circulating electron beam be used to study polarization effects in the elastic scattering process. Construction of a prototype target and demonstration of scientific feasibility has been the immediate goal of the group. A collaboration between the Argonne group and a Soviet group of physicists at Novosibirsk is in the initial stages of formation. As currently conceived, a measurement would be

performed at Novosibirsk in two phases during the next two years at the 2.0-GeV VEPP-III electron storage ring.

Two other important initiatives involve electron scattering experiments. One stems from the need to have a good understanding of the nucleon mean-free path in nuclei, information that is essential for the interpretation of many medium energy experiments involving nuclei, in particular results of recent pion absorption studies. The intent of the experiment in progress at the MIT-Bates Laboratory is to provide a much better constraint on the mean-free path by performing (e,e'p) coincidence measurements in the quasifree region for a variety of nuclei. The second involves measurements of pion electroproduction in deuterium and ^3He along the direction of the momentum transfer where the "virtual-pion photo-effect" is expected to dominate. The pion production cross section and energy spectrum are expected to reveal information on the spectrum of virtual pions in nuclear matter. The experiment is in collaboration between the Argonne group and members of the DPhN/HE service at Saclay. The experiment is in progress at the Saclay linear accelerator.

The second major area of concentration in the medium-energy physics program is the study of intermediate-energy and relativistic heavy-ion reactions with nuclei. Here the emphasis is on understanding reaction mechanisms and determining features of the nuclear equation of state at high energy density where qualitatively new phenomena have been predicted. Activities center on major collaborations at the Brookhaven National Laboratory AGS and at the Lawrence Berkeley Laboratory BEVALAC. The AGS experiment (E802) is concerned with particle-production systematics in reactions induced by 15-GeV-per-nucleon ^{32}Si and ^{16}O ions on various nuclear targets. This experiment, the first fully-instrumented heavy-ion experiment at the AGS, represents the initial phase of a program to explore the properties of heavy-ion reactions at the highest energies and target/projectile masses possible with current and planned heavy-ion accelerator beams. Experiments with intermediate-energy heavy ions, i.e. nucleus-nucleus collisions in the energy regime 50-100 MeV per nucleon, are in progress at the LBL BEVALAC. These experiments are of interest because they probe the transition from a region of interactions dominated by collective reaction modes to one dominated by nucleon-nucleon interactions. In each of these collaborations the Argonne group has assumed responsibility for major aspects of the instrumentation development required for the measurements.

Weak interactions at low energy is the third major component of the medium-energy physics program. Much of our understanding of the fundamental weak interaction has come from low-energy experiments. The program in the Physics Division is involved in testing the "Standard Model" of unification of weak and electromagnetic forces as well as searching for phenomena that signal physics beyond our present understanding. The search for neutrino oscillations at LAMPF is a major activity of the Argonne group. The experiment (E645) is a collaboration with physicists from Caltech, Los Alamos, Ohio State University and Louisiana State University. The Argonne group has been responsible for the design, construction and operation of the active cosmic-ray shield for the neutrino detector used in E645. In an ancillary activity, the Argonne group is operating the shield in conjunction with a large shower detector array of the Cygnus group at Los Alamos to study high-energy cosmic-ray point sources. Measurements of free-neutron beta decay are carried out at the Institute Laue-Langevin in collaboration with scientists from the Institute and the University of Heidelberg. The objective of these studies is to provide the best

determination of the weak-interaction coupling constants. Argonne scientists also study beta decay in light nuclei. A new measurement of the partial decay rate of ^{10}C will further constrain the vector coupling constant which determines the Cabibbo angle. Measurements of the decay of polarized mirror nuclei such as ^8Li are planned as tests for the presence of induced currents and to provide new estimates of the strength of the vector coupling constant.

For the ANL medium energy group, approximately 50% of the manpower and resources of the program are devoted to studies of subnucleonic effects in nuclei which include the muon scattering experiment at Fermilab, the polarized target development for the e-D scattering experiments at Novosibirsk, and the electron-scattering experiments at SLAC. About 30% of the program resources are dedicated to weak-interaction studies and the remainder to studies using intermediate- and relativistic-energy heavy ions. Limited engineering and technical support put a very severe limit on the ability of the staff to exploit new initiatives. Technical resources per research man-year of effort are much lower than typical of major research programs in nuclear physics.

In spite of these limitations, we must increase our participation in the design and construction of experimental equipment if we are to make major contributions to the programs at Fermilab and CEBAF. We anticipate collaborating in the construction of an upgraded vertex detector for the Fermilab tevatron muon scattering experiment and in the design of specialized spectrometers for experiments proposed at CEBAF. We propose to provide additional engineering support for the medium-energy program in 1990.

A. NON-NUCLEONIC EFFECTS IN NUCLEI AT MEDIUM ENERGIES

Electron- and muon-scattering experiments were the principal activities during 1987 in the study of subnucleonic degrees of freedom in nuclear matter. Experiment E665, a study of deep-inelastic muon scattering, in progress at the new muon laboratory at Fermilab, passed from a design and engineering activity to experimental checkout and initial data acquisition during the year. The experiment received first production beam from the Tevatron in July in a run which will continue until February 1988. Initial phases of the run were used to tune up the detection system, and subsequent beam has been used to accumulate data expected to yield the first publishable physics from the collaboration. Work continued on two experiments which the Argonne group leads at the Nuclear Physics Facility at SLAC. A major fraction of the analysis of the data has been completed on experiment NE1, a study of electroproduction of the delta in nuclei which had received beam at SLAC the previous year. Redesign and checkout of a new detector package for the 1.6-GeV spectrometer to be used in experiment NE8, a study of photodisintegration of the deuteron at SLAC, was completed. The measurement is scheduled for the beginning of 1988. Members of the medium-energy group, in collaboration with physicists from the atomic physics program, continued efforts to develop a polarized deuterium jet target which is the essential element of experiments planned in electron storage rings. Already, polarizations of H-atoms and fluxes of atom/s have been obtained which correspond to more than an order-of-magnitude improvement over results previously recorded with conventional polarized sources. The first studies of electroproduction of pions in nuclei began during the year with the successful measurement of the pion energy spectrum from deuterium. The experiment is a collaboration at the ALS-Saclay accelerator involving members of the Argonne and Saclay staff. Data acquisition was completed on a study of the nucleon mean-free path in nuclei, a quasifree electron scattering experiment performed at the MIT-Bates Laboratory. Analysis of the results is underway. In addition to the ongoing research, Argonne staff are participating in preparations for experiments at the national electron accelerator laboratory, CEBAF. Staff members submitted four letters of intent for experiments using first available GeV beams, probably in 1993. The topics of the studies include nucleon and delta propagation in nuclei, pion electroproduction in light nuclear systems, and electroproduction of hypernuclei.

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

(D. Geesaman, R. Gilman, M. Green, H. Jackson, S. Kaufman,
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Deep-inelastic muon scattering from nuclei at CERN in the 1970's provided the first convincing evidence that the structure of nucleons is modified in the nuclear medium. This had profound implications on the understanding of nuclear dynamics. Many low-energy nuclear measurements had previously suggested interpretations involving modification of the nucleon structure. However, the muon-scattering data which are sensitive to the incoherent scattering from the quarks in nuclei can indicate the difference between the quark distribution functions in the free nucleon and in nuclei. The conclusion of these studies was that the distribution of the fraction of the momentum carried by the quarks, $F(x)$, is shifted to lower fractional momenta, x . Theoretical interpretations include a possible rescaling of the nucleon size in nuclear matter or the effect of an enhanced meson field in the nuclear interior.

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A new experiment, E665, using the Tevatron II at Fermi National Accelerator Laboratory will provide new information on the nuclear effects on nucleon properties by studying deep-inelastic muon scattering with coincident hadron detection. The key features of this experiment are: 1) an open geometry allowing essentially 4π -hadron detection. 2) A streamer chamber vertex detector for low-energy fragments. 3) Two large-field-volume superconducting magnets, with field strengths of 4 T-m and 7 T-m to provide accurate measurements of the muon and hadron momenta. 4) A particle identification system including a ring-imaging Čerenkov counter which can separate pions, kaons and protons from 7.0 GeV/c to 150 GeV/c. 5) A muon beam energy of 500 to 800 GeV, a factor of two higher than was previously available. This high beam energy makes the experiment particularly suited to the study of the region of $x < 0.1$, where there is little or no data from other measurements.

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 software. Recent Argonne efforts have concentrated on systematic tests of the system concepts, development of scaler and message facilities and implementing monitoring strategies and techniques. As the experiment has moved into the data-acquisition phase, system reliability has become a prime concern. The most serious issues involve the flow of data and control information between the various machines. Data are read in through three front-end PDP 11/34's via CAMAC and FASTBUS. These front ends are linked to a micro-VAX 11 for data concatenation and tape logging. On-line analysis is performed by sampling events on a VAX 11/780. The data-acquisition software is based on the FNAL DA and VAX-ONLINE systems developed at Fermilab.

Argonne is also responsible for a gas-threshold Čerenkov counter C1, which is required for particle identification in the 5-20-GeV/c region. This detector is now in routine operation and has been continuously available for data

acquisition. Work has continued on the study of integrated particle-identification strategies within the experiment.

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.

E665 received beam from June 1987 to January 1988. A substantial fraction of this time was used to check out the apparatus and to study the level-one experimental trigger. All of the elements of the experiment were brought into operation with the exception of the level-two unbiased streamer-chamber trigger. A preliminary streamer-chamber trigger was employed for this run. Data were accumulated with a 500-GeV muon beam on a liquid deuterium target with an integrated luminosity of $10^{36} \text{ (muon-atoms/cm}^2\text{)}$ and a Xenon gas target with roughly a factor-of-three lower luminosity.

During the next fixed-target cycle at Fermilab, higher muon beam energies are expected. The experiment plans to continue A-dependence studies and to obtain high statistics measurements on hydrogen and deuterium at large momentum transfer.

- b. Electron-deuteron Scattering with a Polarized Deuterium Gas Target in an Electron Storage Ring (R. J. Holt, D. F. Geesaman, M. C. Green, R. Kowalczyk, L. Young, and B. Zeidman)

The most powerful method of isolating the charge and quadrupole form factor of the deuteron involves electron elastic scattering from a tensor-polarized gas target in an electron storage ring. At present, the Medium-Energy Group is considering the technical merit and advantages of an invitation to perform this experiment in a collaborative effort at the VEPP-III storage ring at the Institute for Nuclear Physics in Novosibirsk, U.S.S.R.

We have been developing a novel scheme for producing a high flux of polarized deuterium atoms at the ANL Dynamitron facility. This method is based upon spin-exchange optical pumping, and consequently, the two key advantages of this method over conventional polarized sources are: (i) the flux from the source is expected to be limited only by laser power and (ii) low-background gas load to the storage ring.

Fig. III-1. Zeeman transition signals for K (upper panel) and H (lower panel) as a function of incident laser power.

During the past year we have developed a Zeeman transition technique to observe the polarization of K, H and ^2H atoms directly in the spin-exchange cell. The polarized density of K atoms in the spin-exchange cell was increased by an order of magnitude by developing a new technique to match the laser spectrum to the Doppler-broadened absorption spectrum of the K atoms. Thus far, we have achieved a polarization of 15% for H atoms with a flux of 1.2×10^{17} atoms/s. Typical Zeeman transition signals are shown in Fig. III-1 for K (upper panel) and H atoms (lower panel) as a function of laser power.

Our studies indicate that the polarization can be further improved by increasing the laser power, tailoring the laser spectrum further and developing a more reliable method for coating the surface of the spin-exchange cell.

c. Two-body Photodisintegration of the Deuteron in the GeV Region

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The purpose of this experiment is to observe, for the first time, the $D(\gamma, p)n$ reaction above 1 GeV where the reaction is believed to be dominated by subnucleonic processes. For example, a recent meson-exchange calculation performed at Argonne indicates that the cross section should be substantially larger than that expected from arguments based on QCD. From quark-counting rules one would expect the energy dependence of the cross section to go as s^{-11} , where s is the square of the total momentum in the center of mass.

In preparation for this experiment (NE8 at SLAC) an aerogel Čerenkov detector and a sub-nanosecond time-of-flight system were developed for the 1.6-GeV spectrometer detector stack. These additional detectors permit the identification of protons in the presence of pions or positrons. The detector stack was completed and tested with cosmic rays. Software previously used with the 8-GeV spectrometer and software developed for experiment NE1 was modified for use with the 1.6-GeV spectrometer. The experiment was performed in December 1987.

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Fig. III-2. The cross section $d\sigma/dt$ as a function of s . The solid points represent the preliminary results of the present work. The dashed curve has an s^{-11} dependence expected from quark counting rates.

Preliminary results are given in Fig. III-2 where the cross section $d\sigma/dt$ is plotted as a function of s and the dashed curve has the energy dependence of s^{-11} . Clearly, the results above $s = 7.5 \text{ GeV}^2$ are consistent with the s^{-11} dependence given by the quark counting rates. The meson exchange prediction, not shown here, is approximately 3 times larger than the data at $s = 9 \text{ GeV}^2$. These data represent the first example of a reaction involving a nucleus which is consistent with the quark counting rules.

d. Electroproduction of the Delta Isobar in Nuclei

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The electroproduction of the delta isobar in complex nuclei is under study in an experiment which is part of the Nuclear-Physics-at-SLAC (NPAS) program. The 1.6-GeV and the 8-GeV spectrometers have been used to investigate the scattering of medium-energy ($T = 0.5$ to 2.0 GeV) electrons by targets of ^{12}C and ^{56}Fe . The particular feature to be studied in this experiment is the separation of the longitudinal and transverse cross sections at relatively low four-momentum transfer, $Q^2 = 0.1 (\text{GeV})^2$, where the kinematic conditions correspond to those obtained in pion excitation of the delta. Since the excitation of the $(3,3)$ resonance is the dominant feature of both pion and electron interactions at medium energies, an understanding of the nuclear response function requires a detailed knowledge of delta propagation in nuclei. Inasmuch as there are distortions and strong absorption present in pion-induced excitation of the delta, electroproduction is the only way to produce delta-hole excitations uniformly throughout the nucleus and to investigate delta isobar dynamics in the nuclear medium. The data also provide useful limits on the contributions of the longitudinal cross section in the delta region to the integrated Coulomb sum rule. It has been suggested that the apparent quenching of quasifree charge scattering in heavy nuclei is due to the transfer of longitudinal strength to higher excitations because of correlations in nucleon wave functions. The inclusive cross sections per nucleon for C and Fe in the delta region are

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Fig. III-3. Longitudinal and transverse cross sections for C and Fe. The solid curves are theoretical predictions for the tails of the quasifree nucleon scattering. The dotted curves correspond to measured photonuclear cross sections for excitation of the delta.

observed to be equal. Radiative corrections are small at the higher incident energies. Analyses, such as those shown in Fig. III-2 indicate that the longitudinal component is a small fraction of the inclusive cross section for both targets.

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

Pion electroproduction on nucleons bound in nuclear matter may be significantly different from production on free nucleons because of the contributions of higher-order processes involving neighboring nucleons. Such multinucleon processes are a basic feature of nuclear matter and their study can provide useful insights into the properties of nuclear forces. To explore the use of electroproduction as a probe of such processes we have begun a series of experiments at the Saclay electron linac (ALS) to study the reaction in simple nuclear systems. The deuteron has been chosen for the first measurement because it is a simple benchmark nucleus for which theoretical calculations can be made. The experiment received 29 shifts of beam at ALS during the period of July 27-August 10, 1987. As a result of excellent linac and cryogenic target performance, overall beam efficiency was about 95%. Coincident π^+ spectra were measured for LH2 and LD2 targets with a statistical precision corresponding to approximately 5000 pion coincidences per spectrum. The kinematics, beam energy of 650 MeV, energy loss of 300 MeV, electron angle of 36° , pion angle of 34° , correspond to an invariant mass of 1160 MeV for electroproduction on the proton and $Q^2 = 2.5 \text{ fm}^{-2}$. This region is of interest because electroproduction on the proton is predominantly longitudinal for pion emission in the direction of the virtual photon and the pion pole term makes the largest contribution to the cross section. A comparison of the total yield for deuterons and protons will provide a test of the presence of higher-order processes such as exchange-currents which can alter the basic reaction mechanism. The counting rates for both targets and the signal-to-accidental background ratios were close to estimates. Future measurements will include a study of electroproduction at the peak of the delta, i.e. for an invariant mass of $W = 1232 \text{ MeV}$, a measurement of the π^+/π^- ratio in deuterium, and possibly a measurement of π^+ production on the deuteron and the proton for higher Q^2 where theory suggests that effects of pion-exchange currents may enhance rather than quench charged electroproduction.

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- f. Study of Pion Absorption in ^3He 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. Mukhopadhyay,|| E. Piazetsky,¶ R. E. Segel,** C. Smith,§ and J. Watson,‡)

The analysis of experimental data from pion absorption at 165-, 250- and 500-MeV pion kinetic energies by ^3He is the subject of two Ph.D. theses by students at the University of Virginia and Northwestern University. Progress has been somewhat slower than might have been hoped though some preliminary results of the analysis were reported in 1987. The most surprising result is that at the higher energies the angular distribution of the coincident proton-neutron pair from π^- absorption appears to be very similar to that at lower energies with the asymmetry having the same sign. Since the data now span energies from below to above the delta resonance, the essentially constant asymmetry suggests that this process does not have an amplitude that proceeds through the delta resonance.

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

Information on the propagation of nucleons in the nuclear medium is essential for tests of the nuclear many-body problem and for the analysis of many processes, including pion absorption and inclusive proton scattering. In many

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instances, proton scattering of a few degrees and energy loss of several MeV is not relevant to the analysis of the fundamental process. Experiment 83-17 is designed to study this macroscopic attenuation of 170 ± 30 MeV protons in the nucleus by studying the A-dependence of the $(e,e'p)$ reaction.

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 50.1° in coincidence with protons in the BIGBITE spectrometer in the energy range of 120-210 MeV and proton angles of 49.8° , 57.9° , 65.1° , 67.7° and 72.6° . The 49.8° 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.

Analysis of the experiment is underway. The data cover the range in proton recoil momentum from 0-300 MeV/c and excitation energies in the A-1 systems up to 100 MeV. DWIA calculations are in progress for each system. The proton attenuation will be studied in several contexts such as the DWIA and intranuclear cascade models.

B. INTERMEDIATE AND RELATIVISTIC HEAVY-ION PHYSICS

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

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

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

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

- a. Fission and Charged-particle Emission in Nucleus-nucleus Collisions at Intermediate Energy (F. Videbaek, S. B. Kaufman, B. K. Dichter, O. Hansen,* M. J. LeVine,* C. E. Thorn,* A. Pfoh,* W. Trautman,† R. L. Ferguson,‡ H. C. Britt,§ A. Gavron,|| B. Jacak,|| J. Wilhelmy,|| J. Boissevain,|| M. Fowler,|| G. Mamane,¶ and Z. Fraenkel¶)

The momentum and energy transfer in nucleus-nucleus collisions at intermediate energies has been studied in reactions of 100 MeV/u $^{56}\text{Fe} + ^{197}\text{Au}$ at the Bevalac (E-753). This is part of a study in the energy range intermediate between low energies, describable in terms of macroscopic collective variables, and the high-energy regime dominated by nucleon-nucleon collisions. The measurements were carried out in the PAGODA system designed to measure fragments from reactions over a broad range of energies and masses. The setup consisted of an

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array of 6 gas detectors, each with two position-sensitive multiwire detectors and a high-pressure ion chamber. Several of the gas modules were backed by a 3×3 array of CaF_2 phoswich detectors to measure and identify light particles in coincidence with heavy fragments. The mass identification for the present experiment was obtained from the time-of-flight information between the MWPC's combined with the energy measurement in the ion chamber.

Inclusive angular distributions were obtained in the angular range 24° - 120° for masses larger than 50. The differential cross sections are quite similar to those seen in Ne- and proton-induced reactions on Au with similar total energies. For the binary events the analysis concentrated on those with a combined mass of greater than 120, which can possibly be identified with peripheral fission. The total kinetic energy observed for the heavy coincidence partners is consistent with the kinetic energies from fission of a target-like mass 197. The linear momentum transfer distributions were deduced from an event-by-event analysis and is shown in Fig. III-4. The most likely momentum transfer is 2 GeV/c, a value typical for heavy-ion induced reactions above 20 MeV/u. A total fission yield of approximately 50 mb is observed, to be compared with the total yield for the mass range $120 > A > 70$ of 250 mb. The remaining cross section is associated with the so-called deep spallation process which occurs at smaller impact parameters. The fission-like nature of the decay is observed for momentum transfers of up to 2 GeV/c, corresponding to excitation energies up to 600 MeV, as estimated either from a simple peripheral model or from Intranuclear Cascade (INC) calculations which are being pursued. This analysis in terms of INC calculations shows promise in being able to describe the data, and a detailed comparison will tell us more about the limits to conventional compound nucleus formation and statistical evaporation in heavy-ion reactions at intermediate energies.

Fig. III-4. Parallel momentum distribution for binary events with total mass > 120.

- b. Studies of Particle Production at Extreme Baryon Densities
Produced in Collisions with ^{16}O and ^{28}Si Beams at 14.6 GeV/A
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The interaction of heavy ions at relativistic energies can in principle result in the formation of highly-excited nuclear matter in a region of energy density where it is expected that qualitatively new phenomena may occur. Many questions exist as to the exact energy densities that can be achieved in such collisions and as to the experimental signatures of the expected new phenomena. The objective of this experiment, the first fully-mounted heavy-ion experiment at the AGS, is to study semi-inclusive spectra of identified particles (p, π , K, d...) using a single-arm spectrometer. These spectra will be measured under a variety of trigger conditions relating to the energy and multiplicity flow, which are directly related to the impact parameter and thus to the centrality of the collision.

To date the experiment has had three periods of running. In October 1986 a test experiment with portions of the neutral energy detector and multiplicity array was run with a 14.6-GeV/A ^{16}O beam. The results of this experiment indicate that, for central collisions with moderately heavy targets, complete stopping of the projectile occurs with a consequent energy density of approximately 0.8 GeV/fm³ being reached in central collisions with Au targets. This value is about one-half that obtained in similar experiments at CERN with 200-GeV/A ^{16}O beams. A short data run with the complete apparatus took place in April 1987 with 14.6-GeV/A ^{28}Si , followed by a 3-week production run in November 1987.

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Data analysis from the Spring 1987 run is currently well advanced. Excellent separation between pions and kaons in the spectrometer was achieved using time-of-flight information. Preliminary information on the yields of positive and negative pions and kaons at mid-rapidity indicates a much larger ratio for K^+/π^+ than for K^-/π^- , the former value being higher than expected from nucleon-nucleon data. The K^+/π^+ ratio also exhibits an A-dependence being smaller for the lighter targets. This result is not understood at present but clearly shows the influence of the nuclear medium, either in the initial collision phase or in the later expansion phase through rescattering.

During the running periods we assumed the overall direction of the calibration and running of the zero-degree calorimeter. This is an iron calorimeter, subtending a small angular range centered at zero degrees. The detector was set up and calibrated using 10.4- and 14.6-GeV/A ^{28}Si . An energy resolution of $\Delta E/E = 0.87/\sqrt{E}$ was obtained using empirical gain-matching techniques for the 16 scintillators and phototubes which view the calorimeter. Investigation of the correlations between the energy deposited in the calorimeter and transverse neutral energy and multiplicity show, for the heavier targets, a one-to-one correspondence between large transverse energy and multiplicity (central collisions) and an almost total absence of energy deposited in the calorimeter. Furthermore, for events which do result in significant energy at zero degrees, a simulation of the fraction of the projectile which does not interact with the target under simple geometrical assumptions is able to give a good account of the observed spectrum. This analysis leads us to have confidence in our ability to identify central and non-central collisions and in our estimates of the energy densities achieved in the collision.

The Argonne group has had the responsibility of coordinating the electronics signals from the various partitions of the experiment and of constructing the logic and hardware for the on-line triggering. Work has been done on the conceptual design of a generalized trigger supervisor, computer controlled through a VME interface. Such a device will control and coordinate the first- and second-level triggers for up to 16 partitions, each with 8 trigger possibilities. Triggers can be individually enabled and down-scaled. The hardware for this device is currently being constructed and will be used in the next run scheduled for Spring 1988. We also were responsible for implementing that portion of the data-acquisition software which handled the control and

readout of the three Fastbus crates used in the experiment. Code was written to perform different tasks during on-spill, off-spill, and for testing hardware. This code is loaded into the Fastbus Segment Managers to permit rapid context switching.

The off-line analysis for the experiment is setup within the framework of "Analysis-Control", a software package taken over from the CDF experiment at FNAL. It has been modified to handle the calibration and data structures of our experiment. It allows for flexible definition of which sections of software to execute in a given analysis session and defines a uniform interface between the control program and the partition software. This is a crucial point for a large experiment with many people writing the analysis software. It is also well suited to run on an ACP node which will be used for analysis of the data at ANL and BNL.

- c. Complex Fragment Emission in Nucleus-nucleus Collisions at Intermediate Energies (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†)

The new Pagoda detector system is being used to study the mechanisms of complex fragment emission in the Nb-Nb and Nb-Au systems at energies of 50 and 100 MeV/A in a Bevalac experiment (E-873). A forward-angle hodoscope will be used to detect projectile fragments, an array of gas detectors (multi-wire proportional counters and ionization chambers) will detect medium-mass and heavy fragments, and scintillator phoswiches will measure the light energetic charged particles. Thus, we can study fragments emitted from the projectile and target remnants as well as the participants in these nucleus-nucleus collisions, and search for evidence of multifragmentation. The projectile energies are in the transition region between the low-energy regime describable in terms of potentials and macroscopic variables and the high-energy regime dominated by nucleon-nucleon interactions. In studying these complex processes it is essential to perform exclusive measurements, that is, to measure the correlations between coincident fragments, to measure the light charged-particle multiplicity as a signature for central collisions, and to detect any projectile fragment remnant at forward angles as a signature for a peripheral collision. We expect that the results of these experiments will provide new tests for current theoretical models of heavy-ion reactions at intermediate energies. The first set of data was obtained for the Nb - Au system in December 1987. A typical two-dimensional singles spectra obtained using the Pagoda gas detectors (see the following contribution) is shown in Fig. III-5. The detection and separation of fission fragments, heavy residues and intermediate mass fragments is demonstrated.

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Fig. III-5. Proportional chamber signal and ion chamber signal plotted vs. measured time-of-flight in a gas detector at 36° for the reaction $^{93}\text{Nb} + ^{100}\text{Au}$ at 100 MeV/u.

- d. Calibration of Detectors Used in the Pagoda System
 (B. K. Dichter, S. B. Kaufman, F. Videbaek, H. C. Britt,* D. J. Fields,* M. M. Fowler,† M. N. Namboodiri,* T. C. Sangster,* and J. Wilhelmy†)

The Pagoda detector system, which was first used in Bevalac Experiment E-753, consists of gas detectors, multi-wire proportional counters (MWPC's) and ionization chambers, backed by inorganic/plastic phoswich scintillator detectors. The gas detectors were sensitive to heavy fragments with $Z > 20$, and measured their mass by time-of-flight and energy, while the phoswich detectors could identify light ($Z < 6$) energetic-charged particles which penetrate the gas detector. Improvements on the design of these detectors have been made in order to increase the particle identification capability and to lower the thresholds in charge and energy. A signal is now taken from the low-pressure drift region between the two MWPC's, operating as a proportional counter, and providing additional particle identification. The window between the rear of the gas detector and the phoswiches has been eliminated by constructing a vacuum-tight box to hold the latter. The MWPC design was changed to the new configuration developed at ANL by B. Wilkins and D. Henderson, in which the central wire-grid anode was replaced by a foil cathode, resulting in considerable improvement in timing. The new detectors were tested and calibrated at the LBL 88-inch cyclotron this year, and will be used in the Bevalac experiment E-873.

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C. WEAK INTERACTIONS

The main goals of the weak-interactions program are to verify the implications of the Standard Model and to discover its inadequacies.

Production data runs for the neutrino oscillations were conducted during the three LAMPF running cycles in 1987. The data are of high quality and we expect significant sensitivities to neutrino oscillations in the final analysis.

The cosmic-ray shield built by ANL for the neutrino-oscillation experiment now serves as a muon detector in a search for cosmic-ray point sources. The shield is used to enhance the signal of showers produced by high-energy photons. This realm of astrophysical observation is extremely exciting and there are possibilities that new physics is behind the production of some point-source signals. Prototypes of new airshower array counters are being developed to allow an inexpensive expansion of the Cygnus array.

The experimental study of neutron beta decay is a developing part of the program. In the past we obtained the most precise value of g_A/g_V from measurements of the asymmetry parameter. This year we finished a direct measurement of the neutron lifetime to 2%. The new lifetime measurements are consistent with the old asymmetry measurements if we take the value of g_V from $0^+ \rightarrow 0^+$ superallowed beta decay. In addition to the consequences for weak interaction theory this work has important implications for astrophysics and cosmology.

To better determine the vector coupling constant which determines the Cabibbo angle we are measuring the partial decay rate of ^{10}C to the excited 0^+ level of ^{10}B . In the context of the Kobayashi-Maskawa theory a precise value of this fundamental parameter can be used to determine the number of generations of quarks and leptons. Other experiments to measure g_V in mirror beta decay are being developed.

Finally, our interest in searching for new particles continues. This year we completed a search for axions from neutron capture on protons using the apparatus to study neutron beta decay. In recent years we searched for magnetic monopoles and light Higgs particles.

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

Experiment E-645 is a search for $\bar{\nu}_e$'s produced in the LAMPF beamstop. The beamstop is a copious source of ν_μ , $\bar{\nu}_\mu$, and ν_e but a $\bar{\nu}_e$ signal would suggest a transition from one of the other neutrino types. The detector system is a 20-ton tracking detector made from 40 layers of liquid scintillators and 80 layers of proportional drift tubes. The inner 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 Argonne National Laboratory. The entire system is operated in a tunnel, eventually under 2500 g/cm² of overburden, about 20 meters from the LAMPF beamstop. The $\bar{\nu}_e$ detection method is inverse beta decay on the proton and the experimental signal is the final-state positron (maximum energy about 52 MeV). Each scintillator layer is covered with a thin sheet of gadolinium and an available option is to detect the final-state neutron to reduce backgrounds.

The experiment was exposed to the beamstop neutrino source for three cycles in 1987. The serious neutron background observed in 1986 was dramatically reduced. In 1986 the rate of neutron background was about 0.5 sec⁻¹, but by filling the neutron time-of-flight beam tube with concrete the rate decreased by more than two orders of magnitude. There is no longer any evidence of beam associated neutron background. The cosmic-ray background has been reduced to less than 0.1 event per day of running, below the projections of the original proposal. The first pass analysis of the data from 1987 indicates possible evidence of neutrino interactions with nuclei in the detector but, as yet, no evidence for neutrino oscillations. The projected sensitivity should give use of a limit (assuming no positive evidence is found) at about 1% (90% cl) in

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$\sin^2 2\theta$. With this sensitivity, E645 will be able to confirm or contradict the evidence for neutrino oscillations being reported from experiments at CERN and Brookhaven.

With some repairs and modest upgrades we intend to continue to take data for three LAMPF cycles in 1988, roughly doubling our present statistics.

- b. Search for Cosmic-ray Point Sources (S. J. Freedman, J. Napolitano, B. Fujikawa,* K. Lesko,† and the Los Alamos Cygnus collaboration: University of Maryland, University of California at Irvine, and Los Alamos National Laboratory)

One of the most exciting discoveries in recent years is that certain astrophysical objects are point sources of cosmic-rays. This discovery is expected to be crucial for understanding the mysterious origin of high-energy cosmic rays in general. The Argonne National Laboratory weak-interactions group collaborates with the Cygnus group at Los Alamos which operates a large surface array of plastic scintillators capable of determining the incident direction of cosmic-ray primaries with about 0.5° resolution from the resulting shower-front arrival. This array has recently been expanded to 96 elements spread over a roughly half-mile diameter area. The E-645 active shield is operated in conjunction with the shower array, providing information about the muon content of point-source cosmic-ray showers. Since it is expected that the point-source observations are from high-energy photons, the resulting showers should be muon poor relative to ordinary proton-produced cosmic-ray air showers. Thus excluding showers for which muons are detected should enhance point-source signals.

The E645 shield operated with the shower array for about 5 months in 1987. The data from the shield is now being incorporated into the analysis of events in the Cygnus array. The shield was reconnected to the array after LAMPF turned off in December and we expect to continue to take data until the 1988 running schedule begins.

New detectors for an expanded array are being prototyped at Argonne. The idea is to make a cost-effective array element using liquid scintillators and the

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same hemispherical phototubes used in the E645 shield. The initial prototype, using a simple and inexpensive 55-gallon barrel as a container, gives adequate time and energy resolution with cosmic-ray muons. The scheme will be extended to a larger barrel to give a $1/3 \text{ m}^2$ detector and then to a larger container to a 1 m^2 element. The new detectors can be used either as surface counters or as underground muon counters.

- c. Neutron Beta Decay (S. J. Freedman, M. Arnold,* J. Doehner,* D. Dubbers,† and J. Last*)

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

A technical paper describing details of the PERKEO beta spectrometer was submitted for publication. A detailed paper on the measurements of the beta asymmetry has been accepted for publication.

An improved version of the lifetime experiment, using a chopped beam of neutrons, was developed in 1987. The experiment is approved to run at Grenoble in 1988.

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

The best values of the weak vector coupling constant g_V now come from $0^+ \rightarrow 0^+$ superallowed nuclear beta decay. In principle the best experiment in nuclei is the decay of ^{10}C because of its relative insensitivity to radiative corrections. Unfortunately the experimental error in the branching ratio of the ^{10}C ground state to the 0^+ excited state of ^{10}B is large and the best determinations now come from higher-Z systems. We are remeasuring this

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branching ratio to 10^{-3} with an experiment being conducted at the EN tandem of Western Michigan University in Kalamazoo. The experiment determines the branching ratio from measurements of the cascade γ -rays following beta decay. The critical γ -ray efficiency calibration uses an in-beam method in which inelastic scattering on ^{10}B is used to excite the 0^+ level. By measuring the γ -rays in coincidence with backscattered protons of the right energy, the necessary relative calibration is accomplished in exactly the same geometry as the decay measurement.

The experiment technique was refined in 1987 and some production running was completed at the Western Michigan University Tandem. The statistical error of these measurements is about 0.2%. The analysis is proceeding to determine the value of the branching ratio and the size of the systematic errors. A new procedure for subtracting the background from the pileup of 0.511-MeV annihilation photons using positrons produced in $^{19}\text{F}(p,n)^{19}\text{Ne}$ was developed this year. The reliability of this subtraction is one of the ultimate factors that will limit the final sensitivity. The new procedure seems to work well and we are hopeful that the desired final error of 0.1% can be reached.

e. The Decay of Polarized Mirror Nuclei and the Decay Asymmetry of ^8Li
(S. J. Freedman, J. Napolitano, W. Haeberli,* and P. A. Quin*)

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

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

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

Work progresses on a new detector system for measuring the energy dependence of the beta asymmetry in ^8Li decay. The detector system will be tested at the ANL Dynamitron before it is moved to the Wisconsin Tandem for measurements with polarized ^8Li . This detector will allow us to greatly reduce the statistical and systematic errors of our recent experiment with this nuclear system.

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

In order to explain the sharp positron emission lines seen in particular heavy-ion collisions at the GSI, several theorists have modified the standard axion theory to make the axion a candidate cause of the unexplained phenomena. The new "viable" axion would be very short lived and have a mass larger than two electron masses. A particularly sensitive way to search for this new particle is the isovector transition in $n + p$ capture. The variant axion would produce an e^+e^- emission signal far larger than that expected from ordinary direct-pair emission. Earlier we searched for this enhanced-pair emission during the course of our experiments to measure the neutron lifetime. The analysis of this experiment is now completed. We have measured the pair-decay branching ratio, finding it to be consistent with the predictions of ordinary pair-decay theory, within a 4% experimental uncertainty. A paper will soon be submitted for publication of these results.

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g. The β -decay Spectrum in the $A = 8$ System and the Solar-neutrino Problem (J. Napolitano, and S. J. Freedman, and J. Camp*)

The analysis of the high-energy part of the β -decay spectrum from ${}^8\text{B}$ was completed. This analysis puts the solar neutrino-energy spectrum from ${}^8\text{B}$ on a firm experimental foundation. [The expected neutrino spectrum was deduced from the measured β -decay spectrum, other measurements of the α -decay breakup of the first excited state of ${}^8\text{Be}$, and state-of-the-art theoretical treatments of radiative and recoil order corrections.] A paper reporting this work was recently published.

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h. Determination of ${}^3\text{He}(p, e^+ \nu){}^4\text{He}$ from Measurements of ${}^3\text{He}(n, \gamma){}^4\text{He}$ (S. J. Freedman, J. Napolitano, F. Wolfs, S. Dewey,* and G. Greene*)

The highest energy neutrinos produced in the sun, with energies up to about 19 MeV, come from the weak capture of low energy protons on trace amounts of ${}^3\text{He}$. With solar neutrino detectors capable of measuring neutrino energy now 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 ${}^8\text{B}$ beta decay. Measurements of these ${}^3\text{He}$ 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 ${}^8\text{B}$ neutrinos.

It is not possible to measure the ${}^3\text{He}(p, e^+ \nu){}^4\text{He}$ reaction directly but it is possible to make reliable estimates from the related cross section for ${}^3\text{He}(n, \gamma){}^4\text{He}$ at low energies. At low energies this capture is mostly M1 and thus simply related to the weak process. The experimental value for the neutron capture cross section was obtained in three experiments, two are consistent with $\sigma = 60 \mu\text{barns}$ (the error is about 20%), while one implies $\sigma = 29 \pm 9 \mu\text{barns}$, in disagreement. We have proposed to measure this important cross section to 5-10% accuracy at the ILL. The experiment was recently approved and beam time will be available this summer.

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The experiment is straightforward, and we will measure the cross section using a ^3He -gas target and a large shielded NaI(Tl) detector now being assembled at Argonne. The detector will be calibrated with various reactions including $^3\text{H}(p,\gamma)^4\text{He}$ before shipping the system to Grenoble in the spring.

1. Measurement of the Electric Dipole Moment of the Neutron
(M. S. Freedman, G. R. Ringo, T. W. Dombeck,* J. M. Carpenter,† and J. W. Lynn‡)

The ultimate purpose of this project is to measure the electric dipole moment (EDM) of the neutron. Such a measurement would probably constitute the most sensitive test of time-reversal symmetry now available. Since 1970 it has been clear that this measurement can best be done on ultracold neutrons (UCN) which have a velocity < 7 cm/sec and can be stored in a bottle for several minutes. We propose to do this using a pulsed neutron source. We would keep the inlet to the bottle open only when the pulsed source is on, thus allowing a buildup to an asymptotic density determined by the peak flux of the source instead of the average. This has the advantage that pulsed sources have peak fluxes that are much higher than the average fluxes of steady-state sources of the same average power. Second, we propose to produce the UCN by Bragg reflection of considerably faster neutrons from a moving lattice designed so that the reflected neutrons are almost stationary in the laboratory system. The advantage of this is that it avoids the problems of extracting the very delicate UCN from the different environment near a high-flux source. The present state of the project is that both of these ideas have been tested and shown to be practical, as have several other ideas for enhancing the production of UCN, such as the use of reflectors around the moving crystal and funnels to concentrate the UCN in real space at the expense of their concentration in velocity space.

If the LANSCE neutron source at Los Alamos comes near its design intensity it will be the highest flux neutron source in the world and a good place for this measurement. If it does not, there are other possibilities including IPNS at Argonne. We now believe though we should consider seriously doing the experiment with a UCN interferometer. This offers, in principle, a higher sensitivity

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than the NMR method now being used by other groups. It would certainly have different systematic errors which would make it interesting even if it gave no gain in sensitivity.

Our converter system was set up in IPNS and successfully tested with a horizontal beam and progress was made in understanding neutron guides needed in this system. We propose to improve the converter system by adapting it to use multilayers of Ni and Ti which should be considerably more efficient than mica.

j. Possible Interferometer Designs for Measuring the Neutron Electric Dipole Moment (M. S. Freedman, M. Peshkin, G. R. Ringo, and T. W. Dombeck*)

In one design, we consider the use of an ultracold neutron interferometer with numerous sections having strong electric-field gradients to accelerate the neutrons in one arm. Longitudinally-polarized neutrons with velocity around 3 m/sec and wavelength around 100 nm enter a Mach-Zender parallel-arm interferometer. In the accelerator, a magnetic field perpendicular to the neutron velocity and polarization causes the neutrons to tumble so that the polarization is alternately parallel and antiparallel to the velocity. The tumbling frequency is tuned by varying the magnetic field so that the electric dipole moment is always parallel to the electric field gradient, which alternates in sign as the neutron passes through the accelerator. The neutron's total energy is conserved, but its kinetic energy increases at the expense of its magnetic energy and in proportion to its electric dipole moment. The reduced wavelength results in a phase shift that accumulates over a drift space of several meters. When the beams in the two arms are reunited, there is an observable phase shift proportional to the electric dipole moment.

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

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IV. THEORETICAL NUCLEAR PHYSICS

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

1. Nuclear forces and sub-nucleon degrees of freedom.
2. Intermediate energy physics with pions, electrons and nucleons.
3. Heavy-ion interactions.
4. Variational calculations of finite many-body systems.
5. Nuclear structure studies, principally in deformed and transitional nuclides.
6. Binding of hypernuclei from ΛN and ΛNN forces.
7. Quantum mechanics with magnetic charges or flux lines.

A. NUCLEAR FORCES AND SUBNUCLEON DEGREES OF FREEDOM

(F. Coester, R. B. Wiringa, V. R. Pandharipande,* and Others)

In FY 1987 we completed our calculations of the equation of state of dense matter. Our previous evidence for a possible "pion condensate" in neutron matter remains and we have carefully studied its dependence on the assumed two- and three-nucleon potentials. We have now turned to the application of these results to the properties of neutron stars and to the optical potential for nucleons or holes in nuclear matter.

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

Evidence for subnucleon degrees of freedom from spectroscopic and elastic scattering data is always indirect. In contrast, inclusive deep-inelastic scattering reveals directly the charge- and momentum-carrying constituents. Deep inelastic electron scattering provided the definitive evidence for the existence of quarks and gluons. Recent data on nuclear effects in deep-inelastic lepton scattering are thus of prime importance. We have shown that the dynamics of nucleons and pions with unaltered quark structure can account for the existing data within the experimental uncertainties. We are turning our attention to semi-inclusive processes; these will require improvements in the calculations of the excess pion densities in nuclei.

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

The dense nucleon-matter equation of state (EOS) plays an important role in high-energy heavy-ion collisions, supernovae, and neutron star structure. We have completed theoretical calculations for nuclear and neutron matter for densities ranging from 0.5 to 10 times the nuclear saturation density ρ_0 . These calculations use realistic Hamiltonians that include two-body potentials fit to NN scattering data and a three-body potential fit to the binding energy of light nuclei and the saturation properties of nuclear matter. Variational wave functions and hypernetted-chain equations are used to compute the binding energy as a function of density $E(\rho)$. Significant technical improvements in the evaluation of expectation values have been made in the present study, and a very extensive search in the parameter space of the variational wave functions has been made to optimize the energies.

The chief effect of adding a three-body potential to the Hamiltonian is to significantly improve the saturation behavior of nuclear matter; the models studied here saturate at 1.1-1.2 ρ_0 , compared to $2\rho_0$ for the two-body potentials alone. Consequently, at higher densities nuclear matter is much stiffer. In turn, neutron matter is also significantly stiffer than for two-body potentials only. In one case we see a local softening of the neutron matter EOS near $2\rho_0$ which may indicate a phase transition involving a neutral pion condensate. This is seen in Fig. IV-1 where the solid curve for model AV14+UVII shows a significant break at $\rho = 0.2 \text{ fm}^{-3}$. It is critically dependent on having a realistic two-pion exchange three-nucleon potential present, and is also sensitive to the details of the core of the two-nucleon interaction.

This work has been submitted for publication. The consequences for neutron star structure are discussed below (Sect. A.b.). The nuclear matter wave functions are also being used for a study of the optical potential for application to heavy-ion collisions (Sect. A.c.).

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Fig. IV-1. Neutron matter $E(\rho)$ is shown at low density for five Hamiltonians: AV14 (long-dashed line), UV14 (short-dashed line), AV14+UVII (solid line), UV14+UVII (dash-dot line), and UV14+TNI (dashed line); FP results for UV14+TNI are shown by +'s.

b. Neutron Star Structure Calculations (R. B. Wiringa,
and M. Wolff*)

The results of the dense matter equation of state (EOS) calculations (Sect. A.a.) have been used to study neutron star structure. We have computed the EOS for beta-stable matter including electrons and (optionally) muons. This has been used as input to the Tolman-Oppenheimer-Volkoff equations to compute density profiles for a range of neutron star masses. The maximum supportable neutron star mass is $\approx 2M_{\odot}$ for the nuclear Hamiltonians with a three-body potential, as compared to $\approx 1.5M_{\odot}$ for two-body potentials only, reflecting the greater stiffness of these models. For the case of the canonical $1.4M_{\odot}$ star, we find that the three-body potential results in a correspondingly larger radius of 10-11 km compared to less than 8 km with two-body potentials only. The models with three-body interaction are in good agreement with a variety of current observational data. For example, the stellar mass-radius relations shown in Fig. IV-2 pass within the error limits of the mass and radius determined for the X-ray burst source MXB 1636-536.

In the future we would also like to investigate the superfluid gap in low-density neutron matter which plays an important role in coupling of the neutron star core and crust. This will involve extending the work of Sect. A.a. down to densities of $\approx 0.05 \rho_0$.

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Fig. IV-2. Neutron star mass (in solar mass units) as a function of star radius for: AVI4+UVII (solid line), UVI4+UVII (dash-dot line), and UVI4+TNI (dashed line). Also shown are the TI model (short-dashed line) and PA model (long-dashed line). The box brackets a determination of the mass and radius for the X-ray source MXB 1636-536.

c. Single-particle Potential in Nuclear Matter
(R. B. Wiringa and V. R. Pandharipande*)

The energy-dependent real part of the optical potential for particles and holes in nuclear matter is being calculated for densities ranging from 0.5 to $4 \rho_0$, where ρ_0 is the nuclear saturation density. The optical potential had been studied earlier at densities up to ρ_0 using the variational method and two-body potentials only. Analysis of heavy-ion collisions requires knowledge of the optical potential at higher densities, and the recent work in dense nucleon matter (Sect. A.a.) provides a good starting point for re-examining the problem.

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

In the future we may also re-examine the imaginary part of the optical potential to study the consequences of our more realistic Hamiltonians that include explicit three-body potentials.

d. Variational Monte Carlo Calculations of Few-body Nuclei
(R. B. Wiringa and V. R. Pandharipande*)

Our variational Monte Carlo studies of ${}^3\text{H}$, ${}^3\text{He}$, and ${}^4\text{He}$ are continuing, with several new projects in the discussion stage. At present we are preparing more extensive calculations of nucleon momentum distributions, to compare with the observed $(e,e'p)$ data, particularly the new high-momentum transfer data from Saclay. These require long computational runs to get good statistics, and we now have the necessary computer resources.

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A new area of developing interest is in light-ion reactions such as ${}^3\text{He}(n,\gamma){}^4\text{He}$, ${}^3\text{He}(p,e^+\nu){}^4\text{He}$, and ${}^2\text{H}(d,\gamma){}^4\text{He}$ at astrophysical energies. In previous work the ground state of ${}^4\text{He}$ has frequently been represented by a shell-model wave function. We can do better than this, but we need to learn how to handle the continuum states in a reasonable way.

A major problem is that the current ansatz for the variational ground-state trial function is not able to do as well as the best Faddeev wave functions for the triton, or as the Green's Function Monte Carlo method for the alpha particle. We are planning a detailed study of some simple model problems where good Faddeev wave functions exist to search for improvements to the variational ansatz. Such improvements should carry over to our studies of medium-size nuclei (Sect. IV) and possibly to nuclear matter.

e. Electromagnetic Form Factors of the Deuteron
(P. L. Chung, F. Coester, B. D. Keister,* and W. N. Polyzou†)

Measurements of the deuteron form factors over a wide range of momentum transfer can provide important clues to the role of subnucleon degrees of freedom in nuclear dynamics. For a meaningful calculation of the form factors it is essential that the current-density operators and the deuteron wave function transform under Lorentz transformations in a mutually consistent manner. Standard nucleon-nucleon interactions can be used to construct unitary representations of the inhomogeneous Lorentz group on the two-nucleon Hilbert space. Deuteron wave functions represent eigenstates of the four-momentum operator. Existing parameterizations of measured single-nucleon form factors are used to construct a conserved covariant electromagnetic current operator. The light-front symmetry of the representation allows a clean separation of the effects of one- and two-body currents for arbitrary momentum transfers. We have calculated deuteron form factors with wave functions obtained from the Reid-Soft-Core, Paris, Argonne V17 and Bonn potentials (Fig. IV-3). At sufficiently high momentum transfer we must expect a breakdown of the two-nucleon picture of the deuteron. We find no evidence that this happens for momentum transfers, $Q^2 < 8 \text{ GeV}^2$. A paper for publication has been submitted.

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Fig. IV-3. Deuteron structure function $B(Q^2)$ for different deuteron wave functions and the GK nucleon form factors compared to data. The curve for Bonn Q (not shown) is quite close to that for Bonn R.

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

We have calculated relativistic corrections to the magnetic and quadrupole moments of the deuteron both exactly and by expansion in inverse powers of the nucleon mass. The calculations demonstrate the inadequacy of the expansion. A brief report for publication is in preparation.

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g. Pion Charge Form Factor (P. L. Chung, F. Coester and W. N. Polyzou*)

We have calculated the charge form factor of the pion with relativistic quark-model wave functions, which are spin-zero eigenfunctions of the four-momentum. The results are in agreement with all available data. The confinement radius is much smaller than the charge radius. The relativistic features of the model are essential for the result. A paper for publication is in preparation.

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h. Nuclear Effects in Deep-inelastic Lepton Scattering (F. Coester and E. L. Berger*)

Deep-inelastic lepton scattering by nuclei is a means to observe quark and antiquark distributions per nucleon in nuclei. These distributions are found to depend on the nucleon number A . The ratio of the structure functions $F_2^{\text{Fe}}(x)/F_2^{\text{D}}(x)$ is increased above unity by about 5% for $x < 0.2$ and decreased for $0.2 < x < 0.7$. Earlier uncertainty concerning the amount of small- x enhancement was removed by new data which became available in 1986. The physical assumptions, made to account for the observed nuclear effects, fall into three distinct categories: (1) The assumption of "color conductivity"; it is assumed that quarks migrate between nucleons in the nucleus like the electrons in a semiconductor. (2) The assumption of an independent-particle, or "mean-field" model of nuclear structure. In this approach the structure functions per nucleon of a nucleus are interpreted as structure functions of individual nucleons with properties modified by the medium. (3) Conventional

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nuclear many-body dynamics, this implying the presence in the nucleus of constituent hadrons other than the nucleons, i.e. mesons and isobars. These nonnucleonic constituents contribute to the structure functions of the nucleus, both directly through their own quark structures and indirectly through the momentum balance of all constituents. We have concentrated in the past on the successful development of this last approach. Our review article on this work has appeared in the literature.

i. Excess Densities of Pions in Nuclei (F. Coester)

Any phenomenological meson-nucleon vertex interaction implies a self-energy, which is associated with the nucleon's meson cloud, of the isolated nucleon. The modification of this meson cloud by neighboring nucleons gives rise to nuclear binding and an enhancement (or depletion) of the meson cloud. For a given meson momentum, the mesons are enhanced if the interaction for a momentum transfer equal to the meson momentum is attractive and depleted if it is repulsive. The momentum distribution of the mesons is proportional to the Fourier transform of the two-nucleon density and the matrix elements of a two-body operator that depends quadratically on the form factor of the meson-nucleon vertex. While excess pion numbers in nuclei depend only on the long-range parts of the pion-exchange potential and of the two-nucleon density, the pion momentum densities depend, in an essential manner, on the assumed short-range features of the $NN\pi$ vertex and on the short-range features of the two-nucleon densities.

The sensitivity to such model dependencies was not crucial for our interpretation of the EMC effect, but for the interpretation of future experiments it will be important to establish more precisely the quantitative effects of model assumptions and approximations. We intend to investigate this sensitivity.

j. Quantum Field Theory of Nuclear Dynamics (F. Coester)

Axiomatic quantum field theory provides a useful Poincaré invariant framework for the formulation of nuclear dynamics consistent with the compositeness of the nucleons and the energy spectrum of the physical states. Familiar mean-field approximations were obtained for heavy nuclei. The Poincaré invariance guarantees a consistent treatment of recoil effects in the scattering of protons by light nuclei. The many-body dynamics can be generated from the two-body dynamics. These results will be the subject of an invited paper at the "Workshop on Relativistic Nuclear Many-Body Physics" at Ohio State University, June 6-9, 1988.

B. INTERMEDIATE ENERGY PHYSICS

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

The objective of our research has been the development of a nuclear theory that can describe nuclear phenomena characterized by the excitation of nucleon resonances, such as Δ and $N^*(1470)$, and the production or absorption of on-mass-shell pions. The first part of our work was the extension of conventional nuclear many-body theory to include pion, Δ , and higher mass non-nucleonic degrees of freedom. The main task was the determination of the basic parameters of the theory by carrying out extensive studies of NN reactions up to about 1 GeV and πd reactions up to about 300 MeV. In the past few years we attempted to do this with the assumption that the basic nuclear dynamics can be described by the conventional meson theory of nuclear force. In 1987, we reached the conclusion that the conventional meson-exchange model with N, π and Δ degrees of freedom can account for the main features of the intermediate energy nuclear reactions, but fails to describe the data, which are predominantly determined by the short-range part of the nuclear force. Our current work is focussed on the improvement of our model by using information extracted from various QCD-motivated multiquark models to describe the short-range parts of the NN and $N\Delta$ interactions. The main advance we made in 1987 is the development of a short-range parameterization of the NN interaction based on the information extracted from the MIT Bag model of a six-quark system. We are now examining whether this new approach, supplemented with a more dynamical treatment of meson-exchange mechanisms, will be successful in describing all NN and πd reactions.

The second part of our research is the extension of the above theory to include coupling with the electromagnetic field. In 1987 we constructed a model of $\gamma N \rightarrow \pi N$ for investigating the importance of the final πN interaction, and applied it in analyzing data for the $d(\gamma, p)$ reaction in the GeV energy region. We have also performed a microscopic study of Δ excitation in inclusive (e, e') scattering from ^{12}C .

The third part is a study of the response of heavy nuclei to intermediate energy probes. We have reviewed the surface-response model, which has provided a successful description of quasielastic proton scattering on heavy nuclei. We have also modified this model to describe quasifree pion-nucleus scattering.

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a. Nuclear Hamiltonian with N, π and Δ Degrees of Freedom
 (T.-S. H. Lee and A. Matsuyama*)

The starting point of a microscopic understanding of intermediate energy nuclear reactions is a nuclear Hamiltonian with N, π and Δ degrees of freedom. In the past few years we have investigated the possibility of constructing such a Hamiltonian by extending the conventional meson-exchange

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model of nuclear force to include the coupling to the πNN production channel. Our approach is to assume that the pion production through the Δ excitation can be described by a $\pi N \rightarrow \Delta$ vertex and a $NN \rightarrow N\Delta$ transition potential, while the production through πN nonresonant channels is described by a transition operator $F_{NN \rightarrow \pi NN}$. The validity of the model is determined by carrying out extensive studies of NN reactions up to about 1 GeV and πd reactions up to about 300 MeV. In 1987 we completed this study with the conclusion that the conventional meson-exchange model can describe the main features of the intermediate energy nuclear dynamics, but fails to account for the data which are predominantly determined by the short-range part of the nuclear force. Our results clearly indicate the need for a more fundamental approach to describe the emission of pions from the nucleon and a more realistic parameterization of the NN and $N\Delta$ interactions at short distances. Our findings have been published.

b. Quark Compound Bag Model for NN Scattering Up to 1 GeV
(C. Fasano,* and T.-S. H. Lee)

As a first step in improving the model Hamiltonian described in Sect. B.a., we have developed a parameterization of the NN interaction at short distances in terms of a vertex interaction $H_{Q \rightarrow NN}$ describing the excitation of a six-quark state, Q , with a mass predicted by the MIT Bag Model. We have explored in detail the role of the bag excitation mechanism in determining the relative wave function and the P and S matrices of NN scattering. It is found that the parameters of the vertex interaction $H_{Q \rightarrow NN}$ can be more rigorously determined from the data if the concept of the Chiral/Cloudy Bag model is used to justify the presence of the background meson-exchange interaction inside the bag excitation region. A paper describing our results has been published. The model has been extended to include the coupling with the $N\Delta$ and πNN channels, in order to examine whether this new approach will lead to a satisfactory description of all NN and πd data. The computer program needed for this study is being developed.

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The model has also been used to calculate the three-nucleon force due to pion-exchange between a nucleon and a six-quark bag excited in the collision between the other two nucleons inside the nucleus. It is found that with a simple s-wave oscillator wave function, the contribution of this mechanism results in ^3He being more bound by about 0.1 MeV. A paper describing this calculation is being prepared.

c. Determination of the πNN Form Factor from πN Data (T.-S. H. Lee)

A dynamical model of the πNN form factor is needed for defining more precisely the pion exchange and the nonresonant pion production mechanisms of the model Hamiltonian described in Sec. A.a. It is also needed to answer many pressing questions raised in recent nuclear studies, such as the mesonic explanation of the EMC effect and the electromagnetic production of pions from nuclei. By assuming that the πN dynamics in the P_{11} channel can be effectively described by a vertex interaction $\pi\text{N} \rightarrow \text{N}_0$, where N_0 is a bare particle, and a two-body πN potential, we have constructed an exactly soluble model for a consistent description of both the bound nucleon state and the πN scattering amplitude. The parameters of the model are determined by fitting the data of nucleon mass, πNN coupling constant and low-energy πN scattering phase shifts. The calculated πNN form factor differs significantly from the conventional monopole form. The dynamical consequences of the differences are demonstrated in a calculation of electromagnetic production of pions from the nucleon and the deuteron. A paper describing these results is being prepared for publication.

d. Study of the $\text{N}\Delta$ Interaction in the $\text{NN} \rightarrow \text{NN}\pi$ and $\text{NN} \rightarrow \pi\text{d}$ Reactions
(T.-S. H. Lee and A. Matsuyama*)

Increasing experimental data have suggested that the $\text{N}\Delta$ interaction cannot be described completely by the one-pion-exchange mechanism. To rigorously explore this problem, we have extended our unitary approach to the $\text{NN} \rightarrow \text{NN}\pi$ reaction to account for the interference effect due to the nonresonant pion production mechanism and also to calculate the corresponding $\text{NN} \rightarrow \pi\text{d}$ cross sections. The calculation involves solving a Faddeev-Alt-Grassberger-Sandhas

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scattering equation for the final πNN interaction and a $NN-\Delta$ coupled channel equation including the coupling to the πd state and the nonresonant pion production mechanism. In 1987 we developed the necessary computer programs for this large-scale numerical calculation. A study of $NN \rightarrow NN\pi$ reaction within the Quark Compound Bag model (Sect. A.b.) of NN scattering has been carried out. The results have been reported in an invited paper at the meeting on "Pion-Nucleus Physics" held at Los Alamos, August 1987. We are now carrying out a survey-type analysis of all existing $NN \rightarrow NN\pi$ and $NN \rightarrow \pi d$ data, in order to determine the Δ interaction at short distances.

e. Electromagnetic Production of Pions from the Nucleon
(T.-S. H. Lee and B. Blankleider*)

The production of pions from the nucleon has been conventionally described by a Born term deduced from the Lagrangian field theory and a resonant term involving the excitations of nucleon resonances such as the Δ and $N^*(1470)$. An unsatisfactory aspect of all of the existing models is an on-shell approximation of the final πN interaction. The fit to the data is usually achieved by introducing additional parameters and hence the validity of this conventional model is not fully established. To resolve this problem, we have carried out a study of the $\gamma N \rightarrow \pi N$ reaction with a unitary treatment of the πN final-state interaction. The calculation has been done by using a final πN wave function generated by solving a relativistic three-dimensional Lippmann-Schwinger equation with a driving term deduced from the Cloudy Bag Model and fitted to the πN phase shifts up to about 1 GeV pion laboratory energy. In addition, we have constructed a gauge-invariant Born term which is consistent with our relativistic three-dimensional formulation of the πN problem. Our results show that the usual on-shell approximation is not valid except in the kinematic region dominated by the excitation of nucleon resonances. With appropriate electromagnetic form factors for describing the vertices $\gamma N \rightarrow N$, $\gamma N \rightarrow \Delta$ and $\gamma \pi \rightarrow \pi$, it is found that the model can describe the cross section of the $\gamma N \rightarrow \pi N$ reaction up to the Δ resonance region. We have extended the model to include the excitation of higher-mass nucleon resonances, so that the model can be suitable for analyzing the recent $d(\gamma, p)$ data obtained at GeV energies by the ANL group. Our prediction is compared with a QCD prediction in Fig. IV-4.

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Fig. IV-4. The differential cross section and the reduced amplitude $|f|$ of the $d(\gamma,p)n$ reaction calculated from the meson-exchange model described in Sec. A.e. is compared with the data and a QCD prediction of Brodsky and Hiller.

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

Our primary interest is to examine the extent to which the inclusive $^{12}\text{C}(\text{e},\text{e}')$ data in the Δ excitation region can be understood from the elementary $\Delta \rightarrow \pi\text{N}$ and $\text{N}\Delta \rightarrow \text{NN}$ processes. The calculation has been carried out by using approximations similar to those of Laget. It is found that the main features of the Δ peaks can be described provided that: (a) the strength of the Δ excitation is adjusted to fit the total cross sections of the $\gamma\text{N} \rightarrow \pi\text{N}$ and $\gamma\text{d} \rightarrow \text{np}$ reactions, and (b) the medium effect on Δ propagation is described by an average Δ -nucleus potential deduced from the Δ -hole model of photonuclear reactions. The contribution from the $\text{N}\Delta \rightarrow \text{NN}$ two-body mechanism significantly improves the fit to the data in the "dip" region. The predicted magnitudes in the Δ region are about 20% lower than the data, indicating the importance of more complicated multinucleon processes. Our results are shown in Fig. IV-5. A paper describing our results is being prepared for publication.

g. The Surface Response Model for Quasielastic Scattering
(H. Esbensen)

We have made a review of the surface response model, which has provided a successful description of many features of quasielastic proton scattering on heavy nuclei at intermediate energies from about 300 MeV to 1 GeV. An important characteristic of nucleon-nucleus scattering is the strong absorption in the nuclear medium, which in the model is described by Glauber theory for single-scattering. This determines the overall normalization of the quasielastic cross section and limits the scattering to near the surface of the target nucleus. The nuclear response is simulated by the surface response of semi-infinite nuclear matter, and the basic interaction between the projectile and a target nucleon is described by the free nucleon-nucleon t -matrix interaction. The selectivity of the different spin-isospin responses in (p,p') and (p,n) reactions is discussed. The connection to the distorted-wave impulse approximation that is commonly used in calculations of the cross sections for nuclear states is also discussed.

The model reproduces many features of quasielastic proton scattering, as for example the position and the magnitude of quasielastic peak and its dependence

Fig. IV-5. The calculated inclusive $^{12}\text{C}(e,e')$ cross sections as compared with the data. The dotted and dashed curves are respectively the contribution from the one-body and two-body Δ excitation mechanism.

on target, beam energy and scattering angle. The review was presented as an invited talk at the meeting on "Pion-Nucleus Physics" in Los Alamos, in August 1987 and will be published.

h. Quasielastic Pion-nucleus Scattering (H. Esbensen, E. Siciliano,* and R. Smith*)

We have modified the standard surface response model to describe quasielastic pion-nucleus scattering. The motivation is that there is presently no simple model that can account for the existing quasifree pion data. An important factor in the expression for the quasielastic cross section is the pion-nucleon t-matrix interaction, which we evaluate using an optimal choice for the momentum of the struck nucleon. The pion-nucleon t-matrix is dominated near 200 MeV by the coupling to the delta isobar, and we have also studied the effect of medium corrections by modifying the self-energy of the delta.

The model gives a good description of the position and the width of the measured quasielastic peaks, over a wide range of scattering angles and in particular at the higher beam energies. The magnitudes of the calculated cross sections are also in reasonable agreement with measurements for scattering on heavy nuclei but they are too small for scattering on light nuclei, by a factor of two for ^{12}C . We are presently trying to understand this discrepancy and we intend to make a publication of our investigations.

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C. HEAVY-ION INTERACTIONS
(H. Esbensen, S. Landowne, C. Price, and Others)

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

These studies led to a number of significant results this year. We have developed approximations that enable us to make detailed calculations for heavy-ion reaction problems which have not been studied previously. We have, in particular, investigated two-particle transfer reactions between heavy and deformed nuclei leading to high spin states. The calculated angular distributions exhibit interference patterns which depend sensitively on the angular momentum carried by the transferred particles. We have also made calculations to investigate the consequences for observable cross sections of the newly predicted "diaboloic" pair-transfer process, which occur when there is a band crossing. There are many possibilities for extending these studies; for example, to single-particle transfer reactions, excitations of multiple bands, and collisions between two heavy deformed nuclei.

We have also made significant progress in our ability to confront the low-energy fusion data for medium heavy nuclei. This has been achieved by incorporating the effects of transfer reactions on the fusion process in a way that is consistent with our previously developed higher-order vibrational model. An application to the long-standing problem of $^{58}\text{Ni} + ^{64}\text{Ni}$ fusion has given encouraging results.

a. Higher-order Coupling Effects in Low-energy Heavy-ion Fusion Reactions (H. Esbensen and S. Landowne)

Conventional coupled-channels calculations which take surface-vibrational degrees of freedom into account in heavy-ion collisions make use of linear coupling schemes. Such calculations have successfully described the low-energy fusion cross sections for relatively light and asymmetric mass combinations. They fail, however, for heavier and more symmetric cases, such as Ar + Sn and Ni + Ni. We have applied a second-order vibrational model to Ni + Ni fusion reactions. It is found that the additional higher-order effects are as important as the linear couplings in determining the low-energy fusion cross section. As a result, the agreement with the data is significantly improved, in particular for the symmetric Ni + Ni reactions. There remains, however, a large discrepancy for the $^{58}\text{Ni} + ^{64}\text{Ni}$ reaction, which has been associated with

the influence of couplings to transfer channels. This work has been published.

We have recently extended the higher-order coupling calculations by consistently including transfer channels in the model. We have used empirical shapes for the transfer form factors, with a long-ranged one-neutron form factor and a shorter-ranged direct two-neutron form factor. The strengths of the couplings were adjusted to reproduce the observed transfer cross sections. We have applied the improved model to reactions between the different nickel isotopes and find a significant improvement in the comparison to the low-energy fusion data for $^{58}\text{Ni} + ^{64}\text{Ni}$, whereas the changes for the symmetric Ni + Ni cases are relatively small.

Although the measured cross sections for one-neutron transfer are much larger than those for two-neutron transfer, we find that the coupling to the two-neutron transfer channels has the largest effect on the enhancement of the subbarrier fusion cross section.

b. Heavy-ion Pair-transfer Reactions to High Spin States
(H. Esbensen, S. Landowne and C. Price)

We have initiated a project to investigate transfer reactions in collisions between rather heavy ions with well-deformed nuclei. Such reactions are very difficult to study, both experimentally and theoretically, because of their complicated nature. However, they can provide a unique tool for studying how particle correlations in nuclei depend on spin.

We have developed approximations which allow one to carry out detailed calculations of pair-transfer reactions with heavy deformed nuclei, using a macroscopic model for the transfer interaction. For example, we have calculated angular distributions for the reaction $^{162}\text{Dy}(^{208}\text{Pb}, ^{210}\text{Pb})^{160}\text{Dy}$ to each member of the ground state rotational band up to the spin $I = 26^+$ state. The distributions for the lower spin states show strong interference patterns which are sensitive to the angular momentum carried by the transferred particles (see Fig. IV-6). Within the macroscopic model, this is a reflection of the deformed nature of the target. The interference patterns result from scattering from two different orientations that give the same final spin. Recent experiments done at Oak Ridge have provided evidence for

Fig. IV-6. Differential cross sections for the $I = 4^+$, 6^+ and 8^+ states excited in the reaction $^{162}\text{Dy}(^{116}\text{Sn}, ^{118}\text{Sn})^{160}\text{Dy}$ at the energy $E_{\text{lab}} = 637$ MeV. The points with error bars are the measurements of C. Y. Wu et al. (Oak Ridge). The solid, dotted and dashed curves are the calculations using Coulomb deformation reduction factors of 0.75, 0.80 and 0.85, respectively.

such an effect. Our investigations have resulted in one publication and a manuscript that is in preparation.

c. Testing for Diaboloic Pair-transfer and Berry's Phase
(H. Esbensen, S. Landowne and C. Price)

Recent nuclear structure calculations done at the Technical University of Munich have predicted a new effect that can occur when pairs of particles are transferred at high spins. It is predicted that the pair-transfer amplitude changes sign as one moves through a band crossing. The change in sign is interpreted as a general effect due to Berry's topological phase, which has been discovered in other fields of physics.

We have generalized the macroscopic pair-transfer model to allow for the changes predicted by the nuclear structure calculations. We have made reaction calculations to predict what consequences the new amplitudes have on observable cross sections. The band crossing for ^{160}Dy takes place near spin $I=12$. A reduction of the two-neutron transfer cross sections appears at a final spin that is twice as large. This is in a region where the cross sections are decreasing as a function of spin, even for a Pb beam. The structure effect will therefore be difficult to detect experimentally. Our results have been published.

d. The Rotating Frame and Sudden Approximations for Coupled-channels Calculations (H. Esbensen, S. Landowne and C. Price)

Coupled-channels calculations for reactions between a heavy spherical and a heavy deformed nucleus, which lead to the excitations of high spin states, are in general very difficult and time-consuming due to the large number of coupled equations. We have, therefore, developed and tested various approximations that make it feasible to carry out such reaction calculations. We have demonstrated that the rotating-frame approximation can be derived from a single assumption, which is that the orbital angular momentum is unchanged during the reaction. The number of coupled equations is thereby reduced considerably, with only one equation for each spin state.

In the sudden limit for rotational excitations, where one furthermore ignores the finite excitation energies, the problem reduces to one equation, which has to be solved for different orientations of the deformed nucleus. We have tested both approximations in detail by making comparisons to exact coupled channels calculations, performed for collisions between ^{58}Ni and ^{162}Dy in which high spin states are populated (up to $I = 14^+$). The exact calculations were performed using the computer program PTOLEMY, which was developed at Argonne. The comparisons show that the sudden limit is an excellent approximation for reactions that are dominated by the nuclear interaction. Discrepancies due to the long-range Coulomb interaction can be approximately compensated for by renormalizing the strength of the quadrupole Coulomb field. Our investigations have resulted in two publications.

e. Sudden Limit for the Excitation of Odd-mass Rotors
(S. Landowne and C. Price)

The sudden limit, in which the nuclear orientation is kept fixed during the collision, is the central approximation on which our calculations of heavy-ion transfer reactions with deformed nuclei are based. So far we have considered even-mass systems, which are simplified by having spin-zero ground states. We have, however, formulated the sudden limit for odd-mass nuclei with arbitrary ground state spins. This work is being prepared for publication. It will be the basis for future work on the inelastic excitation of odd-mass rotors and one-particle transfer reactions.

f. One-particle Transfer with Heavy Deformed Nuclei
(S. Landowne, R. Donangelo,* M. Guidry,† and R. W. Kincaid†)

One-particle transfer reactions with heavy deformed nuclei have recently been measured at Oak Ridge. Such reactions can be used to study how single particles are localized on the deformed nuclear surface. We have formulated a semi-classical approach which will be used in connection with microscopic nuclear structure calculations to analyze such reactions.

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- g. Multipair Transfer with Superfluid Nuclei (S. Landowne, C. H. Dasso,* and G. Pollaro†)

Multipair transfer reactions might occur in collisions with superfluid nuclei. A macroscopic approach to this problem has been proposed which exploits the analogy between rotational excitation associated with deformations in ordinary space and pair-transfer reactions associated with deformations in gauge space. This leads to a prediction that the direct transfer of two pairs dominates over sequential pair transfer at low bombarding energies. We have illustrated this with model calculations and by using simple analytic formulas. This work is being prepared for publication.

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- h. Deformation Effect on Low-energy Transfer Probabilities
(S. Landowne and C. H. Dasso*)

In a low-energy collision between two heavy deformed nuclei, the probability of transferring particles should be enhanced relative to two similar spherical nuclei because the surfaces are closer together in the aligned configuration. A simple expression has been derived for the enhancement of the transfer probability. The factor is about 25 for a $^{154}\text{Sm} + ^{154}\text{Sm}$ collision. This work has been submitted for publication.

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D. QUANTUM-MECHANICAL VARIATIONAL CALCULATIONS OF FINITE MANY-BODY SYSTEMS
(S. C. Pieper, R. B. Wiringa, V. R. Pandharipande* and Others)

In the last few years we have been developing techniques and programs for quantum-mechanical variational Monte Carlo (VMC) calculations of the ground states of finite many-body systems. Our long-term goal has been to calculate the ground states of nuclei. We started with calculations of drops of He atoms which have only a simple central potential. These calculations are now complete and we are presently developing a program for the ground states of closed-shell nuclei. We will use realistic two- and three-nucleon potentials such as the Argonne v_{14} and the Urbana model VII potentials which we have already used in calculations of nuclear matter and 3- and 4-nucleon systems (Sect. A.).

We have used our VMC wave functions to make a number of interesting studies of properties of the ground states of many-body systems. In 1986 we completed a study of single-particle orbitals in the drops. Although the calculations are specifically for liquid helium systems, we obtain the many-body results that in some cases are also applicable to nuclei.

This work has been possible only because of our access to the ER Cray. Much of the work for the single-particle orbitals was also done at the Urbana supercomputer facility.

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

We have begun a calculation of the ground-state properties of closed-shell nuclei using realistic two- and three-nucleon potentials. A variational technique is being used with a many-body wave function containing central, spin, isospin, tensor, tensor-isospin, spin-orbit and spin-orbit-isospin two-nucleon correlations. The central correlations and the one-particle Slater determinant are treated to all orders and the non-central correlations are expanded in a cluster decomposition. The $3A$ dimensional integrals (A is the number of nucleons) are done by a Monte Carlo random walk.

At present the two-body cluster part of the calculation is working. We can evaluate the two-body cluster contribution to the ground state energy of ^{40}Ca with an accuracy of ± 0.1 MeV in only a few minutes of Cray XMP time. We are now developing the routines for the three- and four-body clusters. The time per configuration for these clusters will, of course, be substantially greater

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than that for the two-body clusters, but, because the total contribution is expected to be only a few MeV, we will not require the same relative accuracy as for the two-body clusters. Thus the entire calculation looks quite promising.

Once the program has been developed to the four-body cluster level, we will be able to variationally determine the best ground state wave functions. With these wave functions we will be able to calculate observables such as structure functions, densities, and momentum distributions that are relevant for electron scattering and other experiments. Our initial calculations will be for ^{16}O and ^{40}Ca .

b. Single-particle Orbits in Drops of Liquid He (S. C. Pieper, V. R. Pandharipande,* and D. Lewart*)

We have used our ground-state wave functions for drops of liquid ^3He and ^4He to compute wave functions of natural, quasiparticle and mean-field orbitals in these drops. The wave functions of natural orbitals are determined by diagonalizing the one-particle density matrix. The condensate fraction and wave function in the Bose liquid drops are calculated. The quasihole states are defined in the spirit of Landau's theory, and their wave functions are calculated from the overlaps between states containing N and $N-1$ atoms. We find that in Bose drops the wave function of the quasihole orbital is similar to that of the condensate; however, in Fermi drops the quasihole wave functions are different from those of natural or mean-field orbitals. We have developed a simple local-density approximation that provides an accurate relation between the mean-field and quasihole wave functions for both Bose and Fermi drops. The wave functions of natural orbitals are very localized and we have also derived simple methods to construct them from mean-field wave functions (Fig. IV-7). The calculations for the Fermi drops required many hours of Cray XMP time and could not be done with our previous allotment of ER Cray computer time; about 2/3 of the calculations were done on the Urbana Cray with NSF funding.

This work, along with previously reported calculations of momentum distributions in the drops, has been accepted for publication.

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Fig. IV-7. The 3s quasihole orbital in a 70-atom drop of liquid ${}^3\text{He}$ as computed by Monte Carlo (error bars) and by a local-density approximation (solid curve). The dotted curve shows the corresponding natural orbital and the dash-dot curve is the mean-field orbital. In all cases $r^2 \phi^2$ is plotted.

E. NUCLEAR STRUCTURE STUDIES, PRINCIPALLY IN DEFORMED
AND TRANSITIONAL NUCLIDES

(R. R. Chasman, C. E. Price, D. Kurath, and Others)

The principal focus of our research program is the understanding of the effects of strong residual interactions on the properties of nuclear states. When residual interaction effects, based on a spherical basis, are large, many features can be well described by introducing deformation into the single-particle potential. In order to get an accurate description of nuclear behavior in this limit, it is essential to know the spherical single-particle energy-level spacings accurately and to extract the underlying potential parameters. When the residual interaction effects are somewhat weaker, perturbation methods based on either a spherical or deformed central field are difficult to apply and are not very accurate. Here, the problem is to devise methods for treating such states accurately. In our research program, we utilize both deformed potentials and correlated many-body wave functions to study nuclear properties. Our main interests are (1) the development of new many-body methods for obtaining accurate descriptions of nuclear states; (2) the study of nuclear shapes as a function of angular momentum, including the study of the gradual change of nuclear shapes from spherical to slightly deformed along the yrast line at moderate angular momenta, and the study of superdeformation; (3) the study of octupole correlations and octupole (pear shape) deformation in nuclei, which was first predicted in this research program; (4) the study of the competition and coexistence of collective modes at low and moderate excitation energies. With the exception of (1), this research involves close collaboration with experimental programs at Argonne.

The major area of effort this year has been in the development of a new type of correlated many-body wave function that describes residual-interaction correlations well without an excessive number of parameters. The status of this work is that we now have a computer code that allows us to handle considerably more levels than we could previously. In the coming year, we plan to apply this code to a variety of problems. We have also put considerable effort into calculations of the properties of nuclides in the mass region $A \sim 150$ at very high angular momentum. These calculations predict superdeformation in many nuclides of this mass region. They also suggest the likeliest nuclides for experimental investigation. Experimental studies at ANL have shown the existence of a superdeformed rotational band in ^{148}Gd , with properties consistent with the $\sim 2:1$ axis ratio predicted in our calculations. Both the study of superdeformation and the study of new many-body wave functions rely heavily on the use of ER Clay computers.

We are also interested in the ability of relativistic mean-field theories to predict the properties of deformed nuclei. These depend strongly on the nuclear compressibility of the underlying mean-field model. We have found a suitable model that predicts the properties of deformed s-d shell nuclei and spherical nuclei.

Our calculations of nuclear structure effects in $^{12,13}\text{C}(p, \pi^+)$ reactions have led to good agreement with experiment. We have recently completed a calculation in support of an experiment looking for nuclear inelastic Bragg scattering in ^{73}Ge .

a. Many-body Wave Functions (R. R. Chasman)

In many instances, a single-particle picture of nuclear states is not adequate because of the importance of correlation effects. In order to properly describe such states, one must go beyond a single Slater determinant, consisting of either spherical or deformed single-particle states. In the past few years, we have developed many-body wave functions that allow a much improved description of cylindrically symmetric nuclear states. In this approach, the wave-function amplitudes are factored into a product of terms. Each of these factors is an amplitude for a specific configuration consisting of single-particle angular momentum on the z-axis. In this approach, the complexity of the calculation does not go up substantially as the number of nucleons increase. However, the complexity does go up quickly, as the number of levels with a given value of j_z is increased. For eight levels in a group of given j_z , the number of configurations is on the order of 10,000, and each of these has an associated variational amplitude. As there are many values of j_z for single-particle orbitals, the number of variational amplitudes becomes quite unmanageable.

In the past year, we have been exploring ways of simplifying these many-body wave functions, i.e. reducing the number of variational amplitudes. We find that it is possible to further factor the amplitudes describing each configuration of single-particle levels having a particular value of j_z . With this new factoring of amplitudes, the number of variational parameters needed to describe a group with eight levels of a given j_z decreases from ~10,000 to ~1000.

This new approach retains the attractive features of our previously developed many-body wave functions, i.e. (1) the complexity does not go up substantially with the number of particles; (2) it is sufficiently flexible to describe spherical, vibrational and deformed states; (3) parity, particle number and j_z are exact quantum numbers. We plan to exploit these wave functions in studying many nuclear structure problems in the next few years.

- b. Octupole Correlations in ^{227}Ac (R. R. Chasman, H. Martz,*
G. L. Struble,* D. Decman,* R. G. Lanier,* R. Hoff,* D. K. Burke,†
and R. A. Naumann‡)

One of the open questions concerning octupole correlations in nuclides is the extent to which an octupole deformed single-particle potential provides an adequate description of a nuclide, as contrasted with a many-body description. ^{227}Ac is one of the few nuclides with strong octupole correlation effects that can be populated in one-nucleon transfer reactions. We have carried out a calculation of structure factors for the transfer reaction, as well as many-body calculations of the properties of the low-lying states in this nuclide. The experimental studies of this nuclide have been analyzed. We find that the deformed single-particle potential calculation provides a poor description of the transfer reaction cross sections, and of the splittings of the parity doublets in this nuclide. The many-body calculations provide a good description of the splittings of the parity doublets and of the decoupling parameters of the $1/2$ bands, but have not yet been extended to transfer cross section calculations. This study has recently been submitted for publication.

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- c. Competition Between Collective Modes in the Light Actinides
(R. R. Chasman and I. Ahmad)

The interpretation of nuclear structure data in the mass region $A \sim 225$ is a challenging problem. The difficulty is to describe the simultaneous effects of weakly- and rapidly-changing collective octupole, hexadecapole and 2^6 -pole particle-hole collective modes together with moderately strong pairing and quadrupole deformation modes on the properties of nuclear states. We plan to use our many-body wave functions to calculate the energies and properties of 0^+ and 1^- states in the even mass nuclides of this region, and the low-lying intrinsic states in the odd-mass nuclides. We shall investigate the effects of these collective modes on gamma-ray transition probabilities and pair-transfer probabilities. At present, there are several outstanding problems in this region, most noteworthy of which are the magnitudes of $E1$ transition rates and cross sections for neutron pair transfer to excited states.

d. High-spin States in the Pb Region (R. R. Chasman and R. V. F. Janssens)

The nuclide ^{208}Pb is considered to be a good closed-shell nuclide. However, the observed spectra of the neighboring nuclides are considerably shifted from the simple single-particle spacings by residual interaction effects. Several other groups have carried out calculations on this problem, with somewhat conflicting results. We have started calculations with our new many-body wave functions in this region. Because we can now handle more levels, it is now feasible to study the Pb region. It appears that we can get rid of many of the uncertainties in the single-particle spectrum by utilizing experimental data on high-spin oblate states near the yrast line in nuclides near ^{208}Pb . These states will be studied with heavy-ion reactions using the ATLAS facility at Argonne. We plan to use the results of this analysis to determine optimum single-particle potential parameters for nuclides in the Pb region and to apply the potentials so determined to an investigation of superdeformation in the Pb region.

e. Superdeformation in the Rare Earths (R. R. Chasman)

The discovery at Daresbury of discrete transitions in a superdeformed band in the nuclide ^{152}Dy , with a deformation of ~ 0.6 ($\sim 2:1$ axis ratio) has given rise to considerable research activity at Argonne and at many other laboratories throughout the world. We have completed calculations of the energy surfaces of nuclides in this mass region, using a cranked Strutinsky calculational method. We have extracted moments of inertia from these calculations that can be directly compared with the experimental studies of high-spin states. We have also started to calculate single-particle matrix elements for the superdeformed orbitals. Experimental studies of single-particle properties will provide a rather stringent test of theoretical treatments of superdeformation that have been used to explain fission isomers in the actinides. The results of our calculations on superdeformation have been recently published.

- f. Superdeformation in ^{148}Gd (R. V. F. Janssens, R. Holzmann, R. R. Chasman, I. Ahmad, B. Dichter, H. Emling, T.-L. Khoo, W. C. Ma, M. W. Drigert,* U. Garg,* P. J. Daly,†, Z. W. Grabowski,† M. Piiparinen,† W. Trzaska,† J. Borggreen,‡ and D. C. Radford§)

One of the questions actively being pursued in the area of superdeformation studies is how many and which nuclides near ^{152}Dy show superdeformation. Our calculations indicate that ^{148}Gd should also be superdeformed, with a superdeformed minimum about as deep as in ^{152}Dy . The calculations also predict that there are several single-particle levels just above the last occupied neutron level in ^{148}Gd . This is different from the situation in ^{152}Dy where there is a large gap between occupied and unoccupied levels for both protons and neutrons in our calculations. The effect of this difference would be to make it much more difficult to see discrete transitions between members of superdeformed rotational bands in ^{148}Gd than in ^{152}Dy . Accordingly, the search for superdeformation in ^{148}Gd was made by studying continuum gamma-gamma correlations. In this method, a moment of inertia is directly determined from the width of the valley along the diagonal in the gamma-gamma correlation plot. This experiment has been carried out successfully. The observed moment of inertia is in excellent agreement with the calculation and is consistent with an axis ratio of $\sim 2:1$. This work has been written up and accepted for publication.

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- g. Systematics of Light Deformed Nuclei in Relativistic Mean-field Models (C. E. Price, R. J. Furnstahl* and G. E. Walker*)

We have investigated the importance of non-linear scalar couplings and vacuum fluctuation corrections in a relativistic mean-field description of nuclear structure by considering the equilibrium deformations of non-closed-shell nuclei. The σ - ω mean-field model provides a good description of nuclear structure for spherical nuclei; however, this simple model predicts equilibrium deformations that are significantly smaller than those found

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experimentally. It has been argued that this is due to the large value of the nuclear compressibility that is predicted in this model. By including non-linear scalar meson couplings and vacuum fluctuation corrections it is possible to obtain many model parameter sets which reproduce the results from spherical nuclei but have different values of the compressibility. We found that there is essentially no correlation between the compressibility and the deformation in this model. The important quantity for determining the equilibrium deformation is the size of the spin-orbit splitting. By choosing a parameter set which predicts spin-orbit splittings close to those found experimentally, we are able to obtain good representations of deformed nuclei in the s-d shell. In fact, the results from the relativistic calculations are almost identical to earlier predictions from non-relativistic Skyrme models. The essential conclusion from this work is that the relativistic mean-field model can provide a good description of deformed nuclei using parameters that also reproduce spherical nuclei. At present the calculations have been limited to even-even nuclei for simplicity; however, work is in progress to extend the calculations to odd-mass nuclei.

h. Nuclear Structure in the (p, π^+) and $(\pi^+, 2p)$ Reactions
(D. Kurath)

Calculations have been carried out with the aim of elucidating nuclear structure aspects of reactions involving low-energy pions. The basic assumption is that the $pp \rightarrow d\pi^+$ channel is dominant in the nuclear reaction as it is in the free case.

Results for the (p, π^+) reaction on ^{12}C and ^{13}C targets led to reasonable agreement with experimental observations. These results have been published.

There are recent exclusive $(\pi^+, 2p)$ experiments with low energy pions wherein the angular correlation between outgoing protons is measured. This determines the L transfer between initial and final states. In particular, the $^{16}\text{O}(\pi^+, 2p)^{14}\text{N}$ reaction to the ground state exhibits more $L = 0$ contribution than is expected from a pure lp-shell space calculation. The observation is probably the result of $(1p)^{10}(2sd)^2$ admixture in the ^{16}O ground state, something which requires a strong tensor force in the $\langle p^2 | V | (sd)^2 \rangle$ interaction.

i. Gamma Transitions in $^{73}_{32}\text{Ge}_{41}$ (D. Kurath)

An experiment is in progress which attempts to find nuclear inelastic Bragg scattering via synchrotron excitation of the 69-keV $7/2^+$ state of ^{73}Ge . An important feature is the branching ratio of decay to the 13-keV $5/2^+$ state relative to the $9/2^+$ ground state.

The energy spectrum and gamma transitions were calculated with the following model:

1. Protons are in states $J = 0^+$ and 2^+ only, with energy separation as in ^{72}Ge .
2. Neutrons are in a $(g_{9/2})^3$ configuration spread over one MeV.
3. The neutron-proton interaction is $V_{np} = K(Q_{\text{prot}} \times Q_{\text{neut}})$ where Q is the quadrupole operator and the strength K is a parameter.
4. One other parameter is the magnetic moment of the proton $J = 2^+$ state.

The result is that parameter values which give the observed level order in ^{73}Ge and a calculated $\Gamma(7/2^+ \rightarrow 9/2^+)$ within a factor of two of observation, give an estimate of the branching ratio, $\text{BR}(7/2^+ \rightarrow 5/2^+)$ of about 7%. The parameter sensitivity, however, can produce a $\pm 5\%$ change.

F. BINDING ENERGIES OF HYPERNUCLEI AND Λ -NUCLEAR INTERACTIONS
(A. R. Bodmer and Q. N. Usmani*)

Studies of the binding energies of hypernuclei and their interpretation in terms of Λ -nuclear interactions are being continued. In particular, during the past year a study of α -cluster hypernuclei with one- and two- Λ hyperons has been published. The results for the hypernucleus ${}^9_{\Lambda}\text{Be} (\equiv 2\alpha + \Lambda)$ confirm the existence of strongly-repulsive ΛNN three-body forces which were previously found to be required for an adequate description of the binding energies of the s-shell hypernuclei and of a Λ in nuclear matter. The results for $\Lambda\Lambda$ hypernuclei show that the force between two Λ s is quite strongly attractive, about equally so as the comparable force between two nucleons. A comprehensive study of the binding energies of the s-shell hypernuclei and of the Λ well depth (Λ binding in nuclear matter) has been completed and accepted for publication. Work is continuing on α -cluster and multi- Λ hypernuclei and in charge symmetry breaking interactions.

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

We are continuing variational calculations of ${}^9_{\Lambda}\text{Be}$ with an α -cluster model: $2\alpha + \Lambda$, making better allowance for the angular momentum dependence of the $\alpha\alpha$ potential. In particular, we are also calculating the energy of the lowest excited (doublet) state built on the first $J = 2^+$ state of ${}^8\text{Be}$. Preliminary calculations indicate an excitation energy of ≈ 3 MeV, consistent with experiment, implying that the state is particle stable (with respect to breakup into ${}^5_{\Lambda}\text{He} + \alpha$ at a threshold 3.5 MeV above the ground state) and that it should decay by γ transition to the ground state.

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

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b. Binding Energies of the s-Shell Hypernuclei and the Λ Well Depth
(A. R. Bodmer and Q. N. Usmani*)

In this work variational Monte Carlo calculations have been made for the s-shell hypernuclei, and the Λ binding energy in nuclear matter (the well depth) has been calculated variationally with the Fermi hypernetted-chain method. A satisfactory description of all the relevant experimental Λ separation energies and also of the Λp scattering is obtained with reasonable central two-pion-exchange AN and ANN forces and strongly-repulsive dispersive ANN forces. For the latter both spin-independent and spin-dependent forms were considered with the spin-dependent form preferred. Such a spin dependence of the ANN force reduces the spin dependence of the two-body AN force by $\sim 1/3$, and correspondingly contributes $\sim 1/3$ to the 0^+-1^+ splitting of the $A = 4$ hypernuclei. However, even this reduced AN spin dependence is quite appreciable and significantly larger than the most commonly accepted values. On the more technical side, a significant feature is the important ANN three-body correlations required by the two-pion-exchange ANN force in the s-shell hypernuclei.

A paper with the above title has been completed and accepted for publication.

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c. Charge Symmetry Breaking AN Interaction (A. R. Bodmer)

From previous work on the mirror nuclei ${}^4_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{He}$ 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.

G. QUANTUM MECHANICS WITH MAGNETIC CHARGES OR FLUX LINES
(M. Peshkin and H. J. Lipkin*)

This work is part of an ongoing investigation of the elementary quantum mechanics of two closely-related classes of systems, those containing magnetic charges and those exhibiting the Aharonov-Bohm (AB) effect. Past results in the monopole problem include: the most general derivation of the Dirac charge quantization law $eg/c = n\hbar/2$, independently of any assumptions about vector potentials, singular or otherwise; analysis of the angular momentum in the electromagnetic fields when both kinds of charges are present, with peculiarities at large and small distances that constrain the theory in significant ways; the identification of a singularity of the points where electric and magnetic charges coincide, which has very general consequences for all monopole theories. Past results for the AB effect include: identification of the roles of angular momentum quantization and of the electromagnetic angular momentum; removal of ambiguities due to the return flux problem, to spurious singularities near the flux line, and to the use of an externally-fixed magnetic field; introduction of the bound-state AB effect; exact solutions of special scattering problems; and an analysis of the angular momentum of cyons, "atoms" consisting of an electron bound to a flux line. Recent work on monopoles has investigated the physics of a magnetic charge moving in a magnetic field produced by electric currents, and has arrived at the Dirac charge quantization from a novel approach in which the electric charge is a dynamical variable instead of an externally-fixed parameter. The main effort in 1987 was concentrated on the implications of the new electron holography experiments on AB effect, especially for the locality of the theory and for quantum mechanics in a multiply-connected region.

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a. Implications of the Electron Holography Experiment on the Aharonov-Bohm Effect (M. Peshkin)

The electron holography experiments of A. Tonomura have confirmed the predictions of Aharonov and Bohm for the scattering of electrons by inaccessible magnetic fields, with high precision. During the past year, we have carried out an analysis of precisely what we learned from those experiments. That question is not usefully viewed as a contest between standard quantum mechanics and some other theory; alternative theories have been proposed, but those of which we are aware are deeply flawed. Rather, the experiment tests features of standard quantum mechanics which have never been tested before because they come into play only when the electron is confined

to a multiply-connected region. In this sense, the Aharonov-Bohm effect is primarily a feature of multiple connectivity and the issue of local or nonlocal effects of magnetic fields is a subsidiary one.

It has often been observed, especially by C. N. Yang and collaborators, that the AB effect provides the unique unambiguous test of the central idea of gauge field theory, that the electromagnetic field is overdescribed by the Maxwell fields, underdescribed by the four-vector potential A , and correctly described by the quantities $\exp\{(ie/\hbar c)\int A \cdot dx\}$. However, the AB effect also raises questions about causality and locality in quantum mechanics: (1) Einstein causality turns out not to be challenged. The causal behavior of the electromagnetic field alone prevents the AB effect from implying superluminal phenomena in any theory in which the dynamics of the free electron are causal. (2) Locality is capable of more than one interpretation. The AB effect is considered by many, following Aharonov and Bohm, to exhibit a fundamental nonlocality in that the motion of an electron is influenced by a remote electromagnetic field. In one sense, that is not true. The electron, no matter how remote, experienced an induced electric field when the magnetic flux was turned on in the past. The AB effect can be ascribed in an objective way to the finite torque due to that induced field. However, if the electron was created as part of a pair after the magnetic field was turned on, the meaning of locality becomes less clear. The same kind of nonlocality is induced by the Pauli principle in quantum mechanics with neither electromagnetic fields nor multiply-connected regions, so it appears to be a feature of quantum mechanics, not specifically of the electromagnetic interaction.

Finally, the Tonomura experiment tests quantum mechanics in a multiply-connected region with no magnetic field. Previous experiments significantly tested only the consequences of changing the magnetic field. In principle, this distinction is important because standard quantum mechanics allows inequivalent representations of the commutation relations in a multiply-connected region, and this is the first experiment that chooses among them. It agrees with the representation by single-valued wave functions.

Part of the work on the implications of the electron holography experiment was presented in an invited paper at the International Workshop on Matter Wave Interferometry, Vienna, 16-18 September 1987. A full report is being prepared for publication.

ATOMIC AND MOLECULAR PHYSICS

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

- (1) High-resolution laser-rf spectroscopy with atomic and molecular beams (W. J. Childs),
- (2) Beam-foil research, ion-beam/laser interactions, and collision dynamics of heavy ions (H. G. Berry, L. Young, and W. J. Childs),
- (3) Interactions of energetic atomic and molecular ions with solid and gaseous targets (E. P. Kanter and Z. Vager),
- (4) Theoretical atomic physics (Currently staffed by Visiting Scientists), and
- (5) Atomic physics at ATLAS and the ECR Source (R. W. Dunford and H. G. Berry)

Experimental highlights of 1987 have been the research programs begun at two new facilities. The "BLASE" facility has enabled numerous high-precision measurements in the field of fast-ion/laser interactions to be made. The ECR source, being built as part of the ATLAS upgrade was turned on in October 1987, and the first experiments were optical observations of charge-exchange collisions. In addition, the molecular-ion geometrical-structure program has measured some new clusters, e.g. C_3^+ , and developed a new "MUPPATS"-type detector called SAM which when used in conjunction with the previous MUPPATS detector, will allow structure determinations of significantly more complex and heavier molecules. Our work on laser-rf double-resonance spectroscopy has brought new understanding, through highly-precise measurements, of spin-rotation and hyperfine interactions in the alkaline-earth monohalides and the group IIIa monoxides.

The past year has been very busy for atomic physics experiments at ATLAS, with experiments on both the Atomic Physics beam line and other beam lines. All the experiments have been coordinated by Dr. Robert Dunford, and have involved a wide range of visitors from Universities and National Laboratories outside Argonne. One set of experiments utilized the deceleration of ATLAS beams for measuring excited-state pickup cross-sections in highly-stripped heavy ions with none, one or two electrons. Ions were thus accelerated to 250 MeV, stripped in the middle of ATLAS, and then decelerated to 90 MeV in the remaining resonators before being directed to the experimental area.

Another initiative of 1987 has been the utilization for Atomic Physics experiments of even lower-energy highly-stripped ion beams from the electron-cyclotron-resonance source (ECR source), which is part of the current ATLAS upgrade. The ECR source has been mounted on a 300-kV platform which allows a wide variation in beam energies of ions from the source. Under the leadership of Dr. Dunford and with the help of additional equipment funds provided for this purpose in 1987, we have constructed a beam-line and associated target/detection systems to take advantage of a one-year period for atomic physics experiments at this unique facility. A few weeks of experimental beam time in 1987 have already brought some useful atomic physics results.

Associated with this ECR source initiative, we have also put together a proposal for longer-range plans for atomic physics using highly-stripped, low-energy ion beams from such a source, particularly when mounted on a high-voltage platform, as at Argonne. The physics projects possible with this type of arrangement form a strong overlap both with experiments of heavy ions using conventional accelerators such as ATLAS at Argonne, GANIL at Caen, GSI at Darmstadt, and also with the heavy-ion storage ring projects which are now in proposal form in the USA and under construction in Europe. Drs. Dunford, Kanter and Berry are keeping abreast of developments in these new beam techniques of heavy-ion physics to ensure the optimal use of our resources for our continuing work in atomic and molecular structure measurements.

Close collaboration continues between Dr. William Childs, Dr. Linda Young and Dr. Gordon Berry on the laser aspects of our programs. In addition, the development of a polarized target for some of the ECR-based projects of Dr. Dunford makes strong use of our expertise in this area, particularly that gained by Dr. Young in her work on a polarized deuterium source.

Our theoretical program has been staffed entirely by visitors during 1987. Prof. Chii-Dong Lin from Kansas State University stayed on a four-month sabbatical from October 1986 through January 1987. Dr. Christopher Bottcher from Oak Ridge National Laboratory, was here for a year until September 30, 1987, and worked closely with Dr. Kanter's group, as well as providing helpful advice for the other areas of research. He also continued his work on numerical methods for relativistic heavy-ion physics. Dr. Gregory Natanson from Northwestern University, visited for three months during the summer of 1987, continuing his work on understanding the evaluation of parameters measured in Coulomb- explosion measurements. Close collaborations with Prof. Jonathan Sapirstein from the University of Notre Dame on the relativistic structures of three-electron systems, which are being measured in several ongoing experiments in our ATLAS program, were extremely fruitful. The collaborative work is continuing on other relativistic atomic systems.

During this year our group has also been responsible for holding two workshops at Argonne, as well as an International Conference held in nearby Lisle, Illinois. On January 12-13, 1987, a workshop on "Opportunities in Atomic Physics using Slow, Highly-charged Ions" was held in the ANL Physics Division. The workshop coordinated ideas in connection with the deceleration of fast ions in accelerators such as ATLAS, plus the operation of an ECR source on a high-voltage platform. The work has led directly to several avenues of research now under Dr. Dunford's direction. He edited the Proceedings of the workshop, which was published in August 1987. Under the leadership of Dr. Bottcher, we organized a workshop on "Supercomputers in Atomic, Molecular, and Optical Physics" on March 16-17, 1987 at the ANL Physics Division. The Proceedings is being published as an ANL report. Dr. Berry chaired the local committee for the International "Symposium on Atomic Spectroscopy and Highly Ionized Atoms" (SASHIA), held August 15-21, 1987 at the Hickory Ridge Conference Centre, at nearby Lisle, Illinois. The conference was sponsored in part by the National Research Council Committee on Atomic Line Spectra, as well as DOE, through our research program, and the National Science Foundation. The Proceedings are being edited by Drs. Berry, Dunford and Young, and will be published as a volume of Nuclear Instruments and Methods.

In October 1987, Dr. Leonard S. Goodman died quite suddenly, after a short illness. Although he had officially retired in 1986, he continued to come to the lab on a regular basis pursuing his goal of precision spectroscopy of excited positronium until the week of his death. His advice and cheerful presence will be greatly missed. He was at Argonne for 40 years, collaborating for much of that time with Dr. Childs in highly successful programs such as precision magnetic-moment measurements, and more lately in laser-rf double-resonance experiments in atoms and molecules.

V. HIGH-RESOLUTION LASER-rf SPECTROSCOPY WITH BEAMS OF ATOMS, MOLECULES AND IONS

The atomic-beam laser-rf double-resonance technique provides a way for making extremely precise measurements of energy splittings in atomic, molecular and ionic systems. When used selectively to study families of related atoms or molecules it exposes the underlying trends clearly and has in recent years been very important in stimulating new ab initio calculations. This iterative process continues to lead to significant improvements in the theory.

We have devoted considerable effort to studying the spin-rotation and hyperfine interactions in alkaline-earth monohalides and more recently, the (isoelectronic) group IIIa monoxides. These have been chosen as a logical starting point for high-precision molecular studies because they are basically ionic systems with a single electron outside closed shells, and therefore relatively approachable theoretically. In addition to measuring the spin-rotation and hfs interactions themselves, the rotational and vibrational dependences have been determined. Performing the rf transitions in an electric field has led to measurement of the electric-dipole moments (through the Stark Effect), thereby stimulating considerable further theoretical efforts. The availability of such high-precision data has recently led to the use of super computers for the ab initio theory with promising results.

The past year began with intensive work to complete our measurements of the hfs of excited metastable levels in singly-ionized europium using the new collinear laser-ion radiofrequency double-resonance apparatus. The precision allowed by our unprecedentedly narrow linewidths made it possible to observe a J-dependent hyperfine anomaly. This is not yet understood theoretically.

Much effort during the year was applied to the study of the structure of the radical ScO. Our results are of sufficiently general interest that we are preparing four papers in collaboration with researchers at Oxford University, M.I.T., Lawrence Livermore National Laboratory, and Arizona State University, each interested in a different aspect of the ScO structure. Features of particular interest are (1) the strong vibrational dependence of the spin-rotation constant due to the presence of low-lying electronic states not predicted by the ab initio theory, (2) the reversed sign of the hfs interaction from that predicted by theory for the excited A doubler- π state, (3) strong perturbations of the $v = 1$ levels in the A doubler- π state, by the nearby A' $^2\Delta$ state, and (4) the first use in a molecular beam of radiofrequency labelling as a technique for positive identification of optical rotational lines even in the presence of strong perturbations.

Some time was spent in collaborative efforts with other groups doing related work on other ions. This included a two-week period at Aarhus University (Denmark) for measurement of hfs in extremely highly-excited states of singly-ionized europium to test aspects of the multiconfiguration Dirac-Fock (MCDF) ab initio theory, and collaborative work at the BLASE collinear laser-ion facility on hfs measurements of excited levels in singly-ionized samarium and scandium.

a. Hyperfine Structure of Metastable Levels in $^{151,153}\text{Eu}^+$ by Collinear Laser-rf Double-resonance Spectroscopy (A. Sen and W. J. Childs)

This work completes the study of the hfs of the excited $4f^7 5d^9 D$ multiplet in $^{151,153}\text{Eu}^+$ by laser-rf double-resonance spectroscopy using the new collinear laser-ion apparatus. The extremely narrow linewidth (60 kHz, FWHM) led to discovery of a strongly J-dependent hyperfine anomaly, which is not yet understood theoretically. The precision achieved for the hfs measurements (typically ± 2 kHz) is comparable to that customary in beam experiments for neutral atoms, and should ultimately be valuable for testing and improving the ab initio theory through several ionization stages. The unique "triplicate" design of the radiofrequency section (by L. S. Goodman) has been recognized as a breakthrough and is being copied by other groups.

b. Precise Isotope-shift Measurements in Eu^+ (A. Sen, J. Bauche,* and W. J. Childs)

The isotope-shift measurements were done concurrently with the hfs work described above in (1). The analysis is now being completed by A. Sen (University of Toledo, Toledo, Ohio), and J. Bauche (Orsay, France). This work will be described more fully when the analysis is complete.

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c. Collinear Laser and Slow Ion-beam Apparatus for High-precision Laser-rf Double-resonance Spectroscopy (A. Sen, L. S. Goodman, and W. J. Childs)

A paper describing the new apparatus in detail has been published. The two features of greatest interest are (a) the very low ion energy (1.35 keV) which allows the ions to spend a long time traversing the rf region leading to extremely narrow linewidths (60 kHz, FWHM), and (b) the "triplicate" design of the rf section which results in a substantial reduction in the rf power required.

- d. Hyperfine Structure of Highly-excited $5p^5 6s$ Levels in $^{133}\text{Cs}^+$
(A. Sen and W. J. Childs)

Doppler-free fluorescence studies of very highly-excited (14 eV) metastable $5p^5 6s$ levels in $^{133}\text{Cs}^+$ have been made with the new low-energy collinear laser-ion apparatus. This work is now being interpreted.

- e. Hfs of Highly-excited $4f^{12} 6s$ and $4f^{12} 5d$ Levels in $^{167}\text{Er}^+$
(O. Poulsen,* L.-U. Anderson,* U. Nielsen,* and W. J. Childs)

In a continuing effort to understand the shortcomings of the multiconfiguration Dirac-Fock (MCDF) ab initio method of calculating the hfs of neutral and lightly-ionized atoms, hfs measurements were made for about a dozen highly-excited metastable $4f^{12} 6s$ and $4f^{12} 5d$ levels in $^{167}\text{Er}^+$ using the collinear laser-ion apparatus at the University of Aarhus, Aarhus, Denmark. One of us (W.J.C.) collaborated in this work for a two-week period in July 1987. The experimental part of the work is now finished, and the results, including the necessary MCDF calculations, will be described when the interpretation is complete.

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- f. A Molecular-beam Optical and Radiofrequency-optical Double-resonance Study of the $A^2\Pi \leftrightarrow X^2\Sigma^+$ Band System of Scandium Monoxide
(W. J. Childs and T. C. Steimle*)

The molecular-beam laser-rf double-resonance method has been used to study the fine and hyperfine structure of the $v = 0, 1, 2$ manifolds of the $X^2\Sigma^+$ electronic ground state of ScO . As in YO , the spin-rotation interaction is found to be very small compared with the contact hyperfine structure, but the situation in ScO is even more extreme. The ordering of the F-levels turns out to be extremely convoluted. Figure V-1 shows, for example, the ordering found for $N=40$, $v=0$. The spin-rotation interaction is found to be

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Fig. V-1. Hfs splittings determined by laser-rf double resonance for the N=40, v=0 levels of the $X^2\Sigma^+$ state of ScO. Note the extreme shuffling of levels near the top of the G=4 manifold. All hfs intervals shown by arrows have been precisely measured.

highly v -dependent indicating the presence of very low-lying electronic states not predicted by the most sophisticated ab initio calculations. These states are considered from a molecular-orbital point of view. A paper covering these topics has been accepted for publication.

g. Identification of Optical Lines in a Molecular Band by rf Labelling:
Application to hfs in ScO , $X^2\Sigma^+$, $v = 1$ (W. J. Childs)

This paper describes how the enormous selectivity of the molecular-beam laser-rf double-resonance method can be used to positively identify or label individual rotational lines (even specific hfs components of such lines) observed in the fluorescence of a molecular beam. The identity of an unknown optical line is determined by measuring (with rf) the hfs of the lower state involved in the transition. The lower-state hfs must be consistent with that predicted by a model Hamiltonian in which the interaction strengths have been adjusted to fit an ensemble of previously identified lines. Once the Hamiltonian has been established, any of thousands of previously unobserved lines can be identified immediately with the method. Analogous techniques have been used earlier for studies in vapors.

h. Perturbations in the $A^2\Pi$ State of ScO (S. Rice,* , R. W. Field,† and W. J. Childs)

This work is a combination of two studies: (a) application at Argonne of the rf labelling method in (7) above to elucidate perturbed optical lines in the $A \leftrightarrow X$ spectrum of ScO and (b) a much lower resolution but more global study of the same perturbations at M.I.T. by Rice as a post-doc under R. W. Field. Figure V-2 shows two of the perturbations studied. The perturbations are very strong and when detailed deperturbation analysis is carried out reveal a good deal about the states involved. The rf labelling method supplies much information unobtainable in the M.I.T. study and allows drawing much stronger conclusions. A joint paper on this work is in preparation.

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Fig. V-2. Fortrat parabola for the $R_{Q_{24}}(N'')$ branch of the $A^2\Pi_{3/2} \leftrightarrow X^2\Sigma^+_{1/2}$ transition in ScO. Strong perturbations from nearby $A'^2\Delta$ levels occur in two regions of N .

i. Inversion of the Hyperfine Levels in the A $^2\Pi$ Electronic State of ScO
(W. J. Childs, T. C. Steimle,* and J. M. Brown†)

Knowledge of the hyperfine structure of the X $^2\Sigma^+$ state of ScO, as described under (6) above, is supplemented with Doppler-free studies of the hfs in the A $\leftrightarrow$ X fluorescence spectrum. This allows the hyperfine structure of the A $^2\Pi$ state to be determined unambiguously. The results show that the ordering of the hyperfine F-levels is inverted from that expected theoretically. This is of great interest, and J. M. Brown of Oxford University has volunteered, as a collaborator, to investigate the theoretical aspects. This work is now underway and will be described when the interpretation is complete.

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VI. BEAM-FOIL RESEARCH, ION-BEAM/LASER INTERACTIONS, AND COLLISION DYNAMICS OF HEAVY IONS

The thrust of our program is the high precision spectroscopic study of ionic species. Experimental studies of this sort provide the most stringent tests of ab initio calculations of atomic and molecular structure. Such studies, however, have been notoriously difficult due to problems in the generation of the ions in an environment suitable for precision studies. Usually production of ions is done via a plasma discharge, an extremely unfriendly environment for high-precision spectroscopy due to interactions between the ions and neutrals (typically 10,000 times more abundant than ions). However, it has been recognized that extraction of the ions from the discharge and formation into an ion beam provides one with a suitable, perturbation-free environment.

Towards this end, in the past year we have completed the design, construction, testing and calibration of an ion-beam laser spectroscopic facility (BLASE). This facility consists of a 20-150 keV accelerator system capable of producing stable, low-energy-spread beams suitable for collinear interaction with an actively stabilized laser. The extremely high stability of the acceleration energy makes this facility rather unique, in that resonance linewidths are dominated by lifetime and transit-time broadening, rather than by ripple on the acceleration voltage.

This facility, so far, has been used to measure hyperfine structure (caused by the interaction of the nuclear dipole and quadrupole moments with the orbital electrons) in singly-ionized samarium, scandium and thulium. These studies have provided challenging data for ab initio atomic theorists, particularly in the case of scandium where it is possible to study correlation effects in the valence electrons.

We have recently observed, for the first time, resolved hyperfine structure in the (0,1) and (1,2) bands of the B-X transition in the N_2^+ molecular ion. With the incorporation of a RF resonance region on the BLASE accelerator system, we should be able to measure X-state splittings with enough precision to observe the nuclear electric quadrupole moment in $^{14}N_2^+$.

- a. Hyperfine Structure of $^{147,149}Sm II$ (L. Young, W. J. Childs, H. G. Berry, C. Kurtz and T. Dinneen*)

As an initial test of the BLASE (Beam Laser) facility (shown in Fig. VI-1) we have studied the hyperfine structure of nine metastable even-parity levels ($E < 15,000 \text{ cm}^{-1}$) and nine odd-parity levels ($E < 32,000 \text{ cm}^{-1}$) in the two stable odd isotopes of singly-ionized samarium, $^{147,149}Sm^+$.

Collinear laser-ion-beam spectroscopy has been used to measure the hyperfine structure (hfs) of nine metastable even-parity levels ($E < 15,000 \text{ cm}^{-1}$) and

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Fig. VI-1. Schematic of the fast ion-beam/collinear laser beam system. The two induced fluorescence regions are separated by a 50-cm long rf excitation region.

nine odd-parity levels ($E < 32,000 \text{ cm}^{-1}$) in $^{147,149}\text{Sm II}$. The mass resolution of 1 part in 350 eliminates spectral congestion due to overlapping lines from neighboring isotopes. The kinematic compression of the Doppler width is essential to obtain the necessary spectral resolution (approximately 20 MHz) to completely resolve hfs. An optical pumping scheme is used to differentiate the upper and lower levels of the observed transitions. The resulting magnetic dipole hfs constants, A , for the even-parity states arising from the $4f^6(^7F)5d$ configuration that are nominally more than pure 90% LS coupled have been analyzed in terms of Sandars-Beck effective-operator theory. The analysis shows that these levels actually contain substantial admixture of open-shell s electrons. This work has been published.

- b. Hyperfine Structure of $^{45}\text{Sc II}$: Experiment and Theory (L. Young, W. J. Childs, T. Dinneen,* C. Kurtz, H. G. Berry, L. Engström and K. T. Cheng†)

Singly-ionized scandium is an interesting atom in which to test ab initio calculations. Like the neutral alkaline earth atoms, it is a quasi two-electron system, making Sc^+ an attractive place to study single-particle and pair-correlation effects as has been done for CaI . In Sc II , the $3d$ and $4s$ orbits compete for the lowest energy, resulting in a number of even-parity metastable states arising from the $3d^2$ and $3d4s$ configurations which are easily accessible by experiment. We have measured hyperfine structure in many levels of the $3d^2$ and $3d4p$ configuration. In addition, multiconfiguration Dirac-Fock (MCDF) ab initio calculations have been made on these levels. The comparison of experimental and theoretical results shows good agreement for the magnetic dipole hfs constants of the singlet states, in both the $3d^2$ and $3d4p$ configuration. However, the MCDF prediction for the triplet states are not even qualitatively correct. The poor agreement for the triplet state appears to be due to the neglect of core polarization in the present MCDF approach. This work has been submitted for publication.

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- c. Hyperfine Structure of $^{164}\text{Tm II}$ (L. Young, N. B. Mansour, T. Dinneen*, K. T. Cheng†)

We have completed measurements of the hyperfine structure of 4 even-parity and 4 odd-parity levels in Tm^+ . So far, MCDF calculations have been performed for the 4 lower-lying even-parity levels arising from the $f^{13}s$ and $f^{13}d$ configurations. Initial comparisons show reasonable agreement for configurations having no unpaired s electron, but enormous deviations for those with an open s-shell. The data are currently being analyzed.

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- d. Collinear-laser Ion Beam Spectroscopy of N_2^+ (L. Young, N. B. Mansour, T. Dinneen*)

Although there have been many investigations of the first negative system in N_2^+ ($B\ ^2\Sigma_u^+ - X\ ^2\Sigma_g^+$) in the past, only one had adequate resolution to observe fine and hyperfine structure and unambiguously measure spin rotation, Fermi-contact and depolar interaction constants. We have repeated the earlier measurements on a limited number of rotational levels in the (0,1) band, and have extended the measurements to the (1,2) band. Figure VI-2 shows some initial results. In addition, we have incorporated a RF resonance region in the BLASE apparatus which should allow us to measure the X-state hfs with enough precision to observe, for the first time, the nuclear electric quadrupole interaction in $^{14}\text{N}_2^+$.

This work has necessitated a substantial overhaul of the BLASE facility, in that the wavelength range of the laser system had to be extended to the UV and a new data-acquisition system was required to control the RF resonance region. This work is currently in progress.

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Fig. VI-2. From the above fluorescence spectrum, we are able to derive a vibrational temperature of 23000 K, using the intensities of R(24) in the (0,1) band and P(11) and P(12) of the (1,2) band.

- e. Lifetime Measurements in Ar IX (L. Engström,* R. Hutton,* S. Bliman,† M. L. A. Raphaelian,# and H. G. Berry)

We have measured the lifetimes of ten levels in neon-like argon, Ar IX. Doubly-charged argon ions were accelerated to 8 MeV at the Argonne Dynamitron, and standard beam-foil spectroscopic techniques were used to measure the time-dependent decay curves of the levels of interest, plus the decays of many of the direct cascades. In order to obtain accurate lifetimes the ANDC method of cascade correction was then applied in the analysis of the 3p levels in Ar IX. The results are found to be in good agreement with recent theoretical values, except for some 3p 3D levels for which significant deviations are observed. Similar discrepancies have also been observed recently (by L. Engström and R. Hutton) in the isoelectronic ion Cl VIII. These results are part of our ongoing work in this isoelectronic sequence, of relevance to several proposed x-ray laser schemes for these neon-like ions.

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- f. Saddle-Point Electron Production (H. G. Berry, T. J. Gay,* R. E. Olson,* V. Irby,* and E. Hale*)

A well-known phenomenon of fast-beam collisions with gas targets is the production of convoy electrons moving at the same velocity as the target projectile. A second peak in the secondary electron velocity distribution should occur close to the velocity of the center-of-mass energy of the beam-gas collision. We have named these "saddle-point" electrons since they are enhanced by the saddle point produced in the potential distribution seen by electrons between the projectile and the target atom. The experiment incorporated a target chamber and detection equipment from the Argonne Dynamitron, and was set up at a low-energy (250-keV) accelerator at the University of Missouri. We measured the relevant (doubly-differential in energy and angle) scattered electrons in collisions of fast protons on a helium gas target. Our results agree closely with the theory of one of us (R. E. Olson). The initial measurements of protons on helium have been reproduced using other gas targets, which show similar confirmation of the theory. Further work is continuing.

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- g. Metastable Lifetime Measurements (E. Trabert,* L. Engström,† R. Hutton,† S. Bliman,# M. L. A. Raphaelian,§ and H. G. Berry)

Several low-lying excited levels in the Mg-like, Si-like and P-like isoelectronic sequences have no electric dipole-allowed transitions to the ground states. For higher ionized members of these sequences, relativistic effects induce electric and magnetic dipole decays, which lead to lifetimes in the microsecond time range. We have used the beam-foil technique to measure these very long-lived decays in argon ions from the Argonne Dynamitron accelerator. These decay times are typically $10^3 - 10^4$ times longer than other allowed decays in the spectral range observed (the vacuum ultraviolet). The greatly-improved signal-to-noise ratio far from the exciter-foil leads to very sensitive measurements of these forbidden decay rates. The measurements are being analyzed and are being compared with recent calculations.

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- h. Doubly-Excited Levels in Al III (M. L. A. Raphaelian,* I. Martinson,† L. J. Curtis,# R. Haar,# and H. G. Berry)

We have used the Dynamitron to accelerate aluminum ions to continue our studies of doubly-excited states in the Na I isoelectronic sequence. After beam-foil excitation of the aluminum ions, we have observed spectra in the range of 600 Å to 2000 Å, where many of the transitions between the highly-excited quartet states are expected. Since most of these states can autoionize through mixing with rapidly-autoionizing doublet states, most of the transitions are weak. However, several transitions have been identified through comparisons with calculations using the Dirac-Fock Grant code. Identifications in this Al III spectrum are continuing. Further work at higher Dynamitron beam-energies has also begun and is expected to lead to classifications within the Al VI, VII and VIII systems.

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

Tightly-collimated beams of atomic and molecular ions with energies variable in the range 0.5-4.5 MeV are directed onto thin (~ 30 Å) foil or gaseous targets. The distributions in laboratory velocities are measured with high resolution ($\sim 0.005^\circ$ and ~ 600 psec) for the resultant ions. The major aim of the work is a general study of the interactions of fast ions with matter, but with emphasis on those aspects unique to the use of molecular-ion projectiles. In particular, we have been able to deduce the structures of the incident molecular ions. These two different aspects of the work are mutually dependent. In order to derive structure information about a given molecular ion, one needs to know details of how the dissociation fragments collectively interact with the target in which the dissociation occurs. Similarly, a knowledge of the structure of the incident molecular clusters is important in understanding the physics of their interactions with the target. Our work therefore began with careful studies involving beams of the simplest and relatively well-understood diatomic molecular ions (hydrogen, helium hydride ions, etc.). Even with these, several new and interesting phenomena have been encountered (e.g., the interactions between the molecular constituents and the polarization oscillations that they induce in a solid target, the marked difference 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 given us a good grasp on 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 the multiparticle MUPPATS detector has enabled us to directly measure the densities of atomic nuclei within small polyatomic molecules. These experiments provide a radically new source of information on the structures and vibrations of molecular ions which has already made significant contributions in guiding theorists.

The bulk of our effort during 1987 was directed toward the study of several polyatomic molecular ions and cluster ions. These studies have enabled us to explore the limits of the present experiments. As a result of this work, a new apparatus has been developed which will permit us to study a much broader set of molecules than has hitherto been accessible. Additionally, these preliminary studies have also afforded us the opportunity to develop new analysis methods for studying molecules with many degrees of freedom.

Some of the highlights in 1987 included:

- a. Stereostructure of Carbon Cluster Ions
(E. Bakke, A. Faibis, E. P. Kanter, L. Tack, and B. J. Zabransky)

The study of small clusters of atoms has been a very rapidly developing field during the past few years. Because of the wide range of physical and chemical properties that these objects exhibit, they represent an entirely new class of chemically active species which are already finding important applications. Despite this intense interest, there is virtually no direct information on the

geometrical forms of small clusters. Thus, the idea of applying Coulomb-explosion imaging to these molecules has generated considerable interest in the scientific community.

Beyond the study of the small hydrides, it had previously been presumed that these techniques would be inapplicable to the study of clusters of identical atoms. Recently however, in our study of C_3^+ , we have demonstrated that these methods can indeed provide important structural information on small, vibrationally-cold clusters. While our analysis is not yet as detailed as the results we have been able to deduce for simple hydrides, we have been able to clearly deduce symmetry features in the cluster geometries.

The major problems in studying clusters are the ambiguities which arise in mapping data from the "velocity-space" (V-space) geometries measured after the Coulomb explosion to the configuration space before the explosion. With our present analysis methods, these ambiguities provide severe restrictions on the regions of configuration space accessible to study. To circumvent this problem for C_3^+ , we have studied the V-space carbon geometries for the molecules C_3^+ , C_3H^+ , $C_3H_2^+$, $C_3H_3^+$, and $C_3H_4^+$ (see Fig. VII-1). Experimental information on the chemical reactivity of $C_3H_3^+$ and $C_3H_4^+$ had previously suggested these species to be predominantly cyclic and linear, respectively. Based on comparison to these "known" structures, our results for C_3^+ showed quite dramatically that the ground state of this ion is not linear, as had been presumed previously. This finding has prompted higher-order ab initio calculations which have now borne out our experimental conclusions. These results have provided the first direct structural information on a small cluster ion.

b. The Geometry of Protonated Methane CH_5^+

(G. Both, A. Faibis, E. P. Kanter, L. Tack and Z. Vager)

Protonated methane is of great interest in several diverse fields because it has been found to play an important role in many chemical reactions in the earth's atmosphere, the interstellar medium and the laboratory. In particular, it has been hoped that it can serve as a tool to map interstellar methane. The structure and vibrational motion of CH_5^+ is quite unique. Furthermore, a neutral analog that could help experimentalists in untangling

Fig. VII-1. Measured distributions for the ratio $R_s = (v_1 + v_2) / v_3$ [$v_1 < v_2 < v_3$], for the carbon fragment ions (all C^{2+}) resulting from the dissociation of 4.5-MeV C_3^+ , $C_3H_3^+$, and $C_3H_4^+$. The ordinate represents the actual number of molecules for the case of C_3^+ . The data for $C_3H_4^+$ are normalized to yield the same integral as the C_3^+ data while the distribution for $C_3H_3^+$ has been arbitrarily scaled. Error bars represent the effect of sampling statistics only. Lines are drawn to guide the eye.

spectral features, does not exist. As a result, despite the intense interest, there is no structural information available for this molecule. Ab initio calculations have considered methane to assume several possible geometries upon protonation. Among the lowest-lying configurations predicted are two possible C_s geometries as well as C_{2v} , C_{4v} , and D_{3h} .

The study of this molecule by Coulomb explosions has provided an extreme test of our analysis methods. Besides being the highest dimensionality problem we've tackled (12 degrees of freedom), the two low-lying C_s structures lack sufficient symmetry to be detected by the various analysis techniques we used. As a result, we resorted to a method of comparing the experimental distributions to the predictions of the various models.

Firstly, representative points were generated by taking each of the 5 model geometries as starting configurations and then "exploding" each by numerical integration to yield a V-space geometry for each model. They were reduced to 12 body-fixed coordinates to represent each model. Next, the molecules were allowed to vibrate around the equilibrium configurations, with varying vibrational amplitudes. Each configuration generated in this way was "exploded" to yield a synthesized V-space geometry. These geometries obtained for the vibrating models were then compared to the 5 V-space points representing the vibrationless models and the model point closest (in 12-dimensional V-space) was chosen as the best model for each synthesized configuration. By varying the vibrational amplitudes, we were able to ascertain that this method was able to clearly identify the correct equilibrium configuration for vibrational amplitude less than 15% in each coordinate. The same comparison of the experimental data to the representative points shows that our data most closely resembles the C_s structures. While we still hope to develop a model-independent method to describe such data, this method has allowed us to somewhat limit the region of 12-dimensional configuration space which must be explored and thus represents an important advance in our analysis techniques.

c. Development of a segmented-anode MWPC

(B. Affolter, A. Faibis, E. P. Kanter, and B. J. Zabransky)

Our experiments with molecules containing protons and 2 or more heavy ions have been severely hampered because of the finite area of the MUPPATS detector. As a result, we have either sacrificed charge state information (as was the case for $C_2H_3^+$) or information about the proton geometries. This has limited our most extensive studies before now to molecules of the form XH_n^+ . For protonated acetylene, although we could make qualitative statements about the structure, we could not obtain either bond length or vibrational information. For the series $C_3H_n^+$, we were limited to studying the carbon geometries only.

In order to alleviate these limitations, we have developed a new detector specifically optimized for heavy ion detection. The new detector is a single stage multiwire proportional counter with a unique anode structure consisting of a plated-through PC board which interweaves 3 non-intersecting "wire planes" onto a single anode board. As a result, the 3 signals observed for each particle are fast anode signals (rather than the slower cathode signals used in the MUPPATS detector). Based upon tests with a small prototype detector using this geometry, we should obtain time resolutions 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. With this new detector, we will be able to separate the heavily ionizing heavy ions from the more weakly ionizing protons (on the MUPPATS detector) and thus be able to improve the detection efficiencies for molecules containing both types of fragments. Additionally, the large area of the new detector ($25 \times 50 \text{ cm}^2$ rectangle) will permit sufficient electrostatic deflections to resolve heteronuclear heavy-ion fragments.

d. Analysis of Multidimensional Data
(C. Bottcher, A. Faibis, E. P. Kanter, G. Natanson, and Z. Vager)

The aim in the analysis of inclusive Coulomb explosion data is to derive a parametrized function describing the probability densities of the correlated nuclear coordinates within a molecule. In our studies of polyatomic molecules with many degrees of freedom, such a complete analysis has not been possible because of several problems. Among these are that there is no trivial way to calculate the spatial configuration within a molecule before explosion from the final V-space coordinates directly. Instead, one must numerically integrate trajectories from assumed configurations. With many degrees of freedom, this is an enormous computational task. For example, for the case of CH_4^+ with 9 structural degrees of freedom for a coarse resolution of 10% in each coordinate, it is necessary to compute 10^9 trajectories. Even with the present supercomputers, this is not practical. Furthermore, when molecules contain identical atoms which occupy inequivalent sites within the molecule, we need to distinguish between these in V-space. A considerable effort was made this year to attack these problems with several differing approaches.

One method, aimed at determining the most probable configuration for each molecule, is to search the n-dimensional V-space to find regions of high density. By defining each detected configuration as a representative model, we determined which of those models had the highest density of nearest neighbors. This serves to restrict the region of V-space which must be studied, however for molecules with high degrees of symmetry, it can be misleading because of the dilution of degenerate maxima upon permutation of the identical particles. This technique is still being explored. By restricting the region of V-space which needs to be probed, the mapping problem will be vastly simplified.

Another technique which is being used for CH_3^+ , NH_3^+ , CH_4^+ , and NH_4^+ is to explore the behavior in V-space along proper symmetry coordinates. Because the explosion of such molecules cannot lower the symmetry of the problem, it was hoped that distributions within the proper coordinate systems should serve as tests of the model symmetries. The results for CH_4^+ (Fig. VII-2) and

Fig. VII-2. Contour plot of the densities in velocity space after the Coulomb explosion of CH₄⁺ using symmetry coordinates. $B_x = (a_{12} - a_{34})/2$, $B_y = (a_{13} - a_{24})/2$, $B_z = (a_{14} - a_{23})/2$, and a_{ij} is the H_iCH_j angle in velocity space.

NH_4^+ (Fig. VII-3) are in agreement with the conclusion of C_{2v} and T_d symmetries of these molecules respectively. For NH_3^+ and CH_3^+ such analyses have demonstrated significantly different profiles of the kinetic energy of out-of-plane motions of the nitrogen and carbon atoms in these molecules. However, it is clear that we need to increase our present data base (presently $\sim 10^4$ molecules) by at least an order of magnitude to derive statistically meaningful results. This should be practical with the new detection system.

For the case of C_3^+ (with only 3 degrees of freedom), we have performed the necessary trajectory computations to compile a complete mapping. The remaining problem of discriminating between ambiguous points in that mapping is presently being attacked. It is hoped that by using the mean structure derived from the unambiguous maps, we will be able to choose among the various ambiguous regions. To properly distinguish between the bent and cyclic forms of this molecule, preliminary studies have indicated that it is necessary to perform relatively expensive Monte-Carlo simulations of loss and capture of electrons in the foil. The accurate utilization of the Monte-Carlo calculations seems to be one of the most important directions in the quantitative interpretation of the data. It follows from the trajectory calculations that our measurements do have a sufficient resolution to make the choice between the cyclic and bent forms of C_3^+ after the charges of the carbons are correctly determined. The results so far indicate a cyclic, but non-equilateral structure for this ion.

e. Ion Source Development

(G. Both, L. Tack, Z. Vager and B. J. Zabransky)

We have investigated various schemes appropriate for sources of state-selected molecular ions in the Dynamitron high voltage terminal. Several experiments have been carried out this year with molecular-ion beams produced by low-energy electron impact in the terminal. Such a source was constructed by modification of the electrode structure of a conventional duoplasmatron ion source. In this mode of operation, electrons were produced by direct heating of the filament, however they were confined to this region by holding fields. Those electrons which drift into the usual plasma region, are accelerated and impact the source gas (at a pressure of about 50 mTorr) in the entrance to the extraction region. The resulting ions are then extracted and

Fig. VII-3. As in Fig. VII-2, but for events resulting from the explosion of NH_4^+ .

accelerated. For our studies of the ions $C_3H_n^+$, this source was used to produce each of the ions in that series by electron impact on allene. Since there exist abundant chemical reactivity data on the daughter ions prepared in this way, we were able to take advantage of this earlier work to characterize our ion beams.

Work was also begun on a photoionization source to select higher-lying vibrational excitations. This source consists of an intense UV lamp to photoionize the sample gas, and a large-acceptance orange peel spectrometer to momentum-analyze the detached photoelectrons and thus tag the resultant ions. A prototype spectrometer was constructed and tested. Although this spectrometer properly focusses high energy electrons, for electron energies below 100 eV the collection efficiency deteriorates severely. The problem now appears to be stray electric fields as a result of the deterioration of the insulation of the conducting segments.

VIII. THEORETICAL ATOMIC PHYSICS

In 1987, the theoretical component of our Atomic Physics program consisted of visitors to aid the different experimental projects. Professor Chii-Dong Lin from Kansas State University was at Argonne from September 1986 through January 1987 and worked on polarization transfer in atomic excited states, plus the many-body problem in both charge-exchange collisions and in atomic multiply-excited states. Dr. Christopher Bottcher from Oak Ridge National Laboratory spent 1987 at Argonne. He worked in part with the molecular-ion structure group, helping with studies of the problems of interpreting the Coulomb-explosion data in terms of the original geometrical structure of the unexploded molecular ions. In addition, he continued his calculational program using various new numerical techniques for studies of ion-atom collisions. He gave lectures on this subject and on the three-body Coulomb problem. Other parts of this latter problem were also studied by Dr. Lin. Dr. Bottcher's work in ultra-relativistic collisions of heavy ions was not directly tied to experimental work in the ongoing experimental programs, but will be relevant to relativistic collision physics. Dr. Gregory Natanson of Northwestern University visited during three months of the summer and worked on the symmetry problems involved in the breakup of molecular ions. During the year we have made substantial efforts to locate a permanent staff member for the theoretical program, but have not yet filled the position. Professor R. Stephen Berry of the University of Chicago has a part-time appointment with the Physics Division, but was on leave at Oxford, U.K. during 1987. We expect increased collaboration with him in the future. We anticipate that Prof. Peter Sigmund (Odense University) will spend a sabbatical year with us in 1989.

a. Theoretical Atomic Physics (C. D. Lin*)

1. Theory of Anisotropy Transfer and Calculations of Alignment of np States Populated in Electron Capture by Highly-Charged Ions

This study involves the analysis of the polarization of light emitted by excited atoms produced in ion-atom collisions or in electron-atom collisions. In this analysis, we need to account for the alignment of the excited states produced in the primary collision as well as the contribution due to the cascade from higher excited states. Thus we must consider the alignment transferred from the higher excited states. In performing the cascade analysis it is necessary to include the effect of spin-orbit interaction which tends to reduce the alignment. A general expression for alignment transfer has been derived and the method has been applied to the analysis of two sets of experimental data. This work has been published.

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b. Coulomb Explosions (C. Bottcher)

We have developed a method of analysis of Coulomb-explosion data which does not require the identification of indistinguishable fragments. Thus, in the case of CH_4^+ the four protons in one event do not have to be aligned with the four protons in any other. Any bias in the analysis can predict spurious structures. CH_4^+ is a good test case to focus on: its ground electronic state has either D_{2h} or C_{2v} symmetry, with calculations predicting a very small energy barrier.

The new approach is to convert the raw data to histograms of the distributions of all simple geometric invariants (e.g. angles between bonds, volumes of tetrahedrons etc.). Such a representation is obviously invariant under all spatial and permutational symmetries. A Monte Carlo technique is then used to generate models which reproduce these histograms. As an example the normal vibrations about a D_{2h} configuration of CH_4^+ have been explored. The analysis suggests a distribution of uncorrelated D_{2h} vibrations, but with large excursions into the C_{2v} valleys. A manuscript is in preparation.

The concept of geometric invariants could be exploited in other problems in chemical physics, which involve structures with ill-defined or "floppy" shapes (the erudite term is "labile"), e.g. ionic clusters.

c. Numerical Methods for Ion-atom Collisions (C. Bottcher and M. Strayer*)

We have continued to develop the Basis-spline collocation method, to the point at which it could be used to calculate capture and ionization in an ion-atom collision. The wave functions of independent electrons are represented on a cartesian lattice in 3 dimensions without further simplifying assumptions. The first results on proton-hydrogen collisions were presented at the 1987 ICPEAC meeting in Brighton, U.K.

The codes as written are applicable to many electron systems, and studies on $(\text{C6}^+) + \text{Ne}$ are under way. Because no restriction to axial symmetry is imposed, applications to simple Coulomb explosions are possible, e.g. $(\text{H}_2^+) + \text{He} \rightarrow$ breakup products. A manuscript is in preparation.

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d. Three-body Coulomb Problem (C. Bottcher)

While at Argonne, we have continued to study the Coulomb three-body problem near the threshold for breakup, using a numerical semiclassical approximation to the asymptotic wavefunctions. Attention focussed on understanding the semiclassical caustics predicted by the theory. These are integrable singularities, analogous to the rainbow in potential scattering and optics. They have been analyzed at two levels: (1) The semiclassical problem was solved analytically near the singularity, as a check on the numerical methods. (2) Higher-order approximations based on path integrals have been calculated. Beyond the lowest order the singularities are softened to finite peaks. A paper on this work will appear soon.

e. Production of Heavy Leptons in Ultra-relativistic Heavy Ion Collisions
(C. Bottcher and M. R. Strayer*)

Substantial progress on this project was achieved during this year at ANL. The expected cross sections for producing muon and tauon pairs at RHIC are large enough to be interesting for observations. We have finally succeeded in expressing the amplitudes as Fourier components of the invariants of the time-dependent electro-magnetic field,

$$\mathbf{E} \cdot \mathbf{E} - \mathbf{B} \cdot \mathbf{B} \text{ (scalar), } \mathbf{E} \cdot \mathbf{B} \text{ (pseudoscalar),}$$

so that our model is automatically Lorentz and gauge invariant.

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IX. ATOMIC PHYSICS AT ATLAS

The Argonne Tandem Linear Accelerator System (ATLAS) is a heavy-ion accelerator which provides an outstanding opportunity for studying the physics of highly-ionized atoms. Atomic physics at ATLAS involves in-house experimenters and outside groups. The experiments have included: X-ray and VUV spectroscopy, studies of atomic collisions, heavy-ion desorption of biomolecules, Auger electron spectroscopy and studies of Rydberg atoms. Prior to 1986 atomic physics experiments were performed using general-purpose beamlines and facilities which were designed for research in nuclear physics, but in 1986 a dedicated atomic physics beamline was set up and this has greatly facilitated the use of ATLAS for atomic physics. Plans are now underway to improve the capability for atomic physics with the addition of a foil stripper and remotely-adjustable slits at the end of ATLAS just before the bending magnet which delivers the beam to the atomic physics beamline. This, combined with the addition of a hall-probe gaussmeter on the switching magnet and a second set of slits just after the bending magnet, will provide the capability for stripping to high-charge states and delivering a specific charge state to the target area. In addition, in the past year, the data-acquisition program at ATLAS (DAPHNE) was expanded to provide the special capabilities required for atomic physics experiments.

An upgrade of the ATLAS facility is in progress (Uranium Upgrade) which will replace the present tandem injector of the linac with an ECR ion source and a new injector linac. The new injector will extend the mass range of ions that can be accelerated up to uranium (heaviest mass currently available is iodine, $M=127$) and it will 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 can be done. In addition, the new injector will allow experiments with more highly-charged ions because useful beam intensities can be obtained from the higher charge states obtained after stripping. The atomic physics program will also benefit from use of the ECR ion source which has been built as part of the ATLAS upgrade. This source provides intense beams of slow, moderately-charged ions and so it is an excellent tool for atomic physics. The source will be available for atomic physics on a half-time basis until it is called upon to begin injecting ATLAS in 1989. In order to take advantage of this opportunity for atomic physics, we have set up an atomic physics beamline next to the source and started an experimental program.

One of the main efforts this year was the setting up of an atomic physics beamline at the ECR ion source. The source was first run successfully in late October and the first atomic physics experiment was begun about two weeks later. The beam line has been set up in a temporary location in the old west target room at ATLAS. It consists of two parts. A fixed section contains collimating, focussing, diagnostic and steering elements. The second part is the experimental area which will change configuration depending on which experiments are underway. In the initial setup a grazing incidence spectrometer is attached to the beamline observing a gas target. The facility also includes a laser lab located adjacent to the beam line which will be used for laser spectroscopy of lower charge-state ions and also to make a polarized alkali target for polarization studies.

A unique feature of our ECR facility is that the ion source is on a 350-kV high-voltage platform. This will provide increased flexibility in the experimental program as compared to other ECR ion-source facilities where accelerating potentials are, at most, 20 kV. The first experiments were measurements of state-selective electron-capture cross sections which utilize the high-voltage platform to extend existing measurements to higher velocity. Other programs which will benefit from the high-voltage platform include: (i) measurements of quasimolecular interferences; (ii) polarization transfer using optically-pumped Na target; (iii) studies of metastable hydrogenlike ions; (iv) studies of polarization obtained by tilted foils; (v) precision laser spectroscopy; (vi) measurements of double charge-transfer cross sections.

In addition to the work at the ECR ion source, we are continuing our program of research on the Atomic Physics Beamline at ATLAS. The experiments have utilized both target areas on the beam line and in addition we have used the Magnetic Spectrograph in target area III. Some of the highlights include the following:

- a. Spectroscopy of Helium-like and Lithium-like Ions (H. G. Berry, A. E. Livingston,* A. S. Zacarias,* Y. N. Lu,* and R. W. Dunford)

A program is in progress to make precision measurements of transition energies in helium-like and lithium-like ions of high nuclear charge (Z). Such measurements provide an important test of quantum electrodynamics and atomic-structure calculations. In the past year a measurement of the $1s2s\ ^3S_1 - 1s2p\ ^3P_2$ transition energy in helium-like nickel $^{58}\text{Ni}^{26+}$ was completed. A preliminary analysis of the data yields a value of $226.21 \pm 0.06\ \text{\AA}$ for the transition wavelength. This result is the most precise measurement of a high- Z two-electron $2s-2p$ transition energy. This measurement is in agreement with the best available theoretical calculation of Goldman and Drake which includes lowest-order screening corrections to the Lamb-shift contribution. In the coming year, these measurements will be extended to higher Z in experiments on helium-like bromine.

The interest in lithium-like ions comes from recent theoretical progress by Johnson and Sapirstein at Notre Dame. Their work, which is still in progress, utilizes many-body perturbation theory. The calculations include, explicit non-perturbative computation of higher-order Breit interaction contributions and should provide the first unambiguous screening corrections to the Lamb-shift contributions in three-electron ions. In order to test these

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calculations, we plan to make high-precision measurements of the $1s^2 2s^2 S_{1/2} - 1s^2 2p^2 P_{3/2,1/2}$ ground-state transitions in helium-like nickel using the 2.2 meter grazing incidence spectrometer. We would then extend these measurements to higher Z using lithium-like bromine.

- b. Lifetime of the 2^1S_0 State of Heliumlike Ni^{26+} (R. W. Dunford, H. G. Berry, K. O. Groeneveld, M. Hass, L. Curtis,* A. E. Livingston,† E. Bakke, M. L. A. Raphaelian)

We have undertaken a measurement of the lifetime of the 2^1S_0 state of heliumlike Ni^{26+} . The 2^1S_0 state is forbidden to decay by single photon emission to the 1^1S_0 ground state because of the requirement that angular momentum be conserved in the decay. The dominant decay mode is the simultaneous emission of two E1 photons. A precise calculation of the decay rate including relativistic corrections was completed in the past year by G. Drake. The only experiment sensitive to the relativistic corrections is a measurement on the 2^1S_0 state in heliumlike Kr^{34+} done at GSI by Marrus et al. which is in disagreement with the theoretical result. Our experimental goal is to resolve this discrepancy by making a precision measurement in Ni^{26+} . The relativistic effects are about 3% in nickel and our goal is to make a measurement at the 1% level.

The first run of this experiment was completed in the past year. A 350-MeV beam of nickel ions from ATLAS was prepared in the $26+$ charge state and directed to a thin carbon target, exciting some of the ions to the 2^1S_0 state. The decay radiation coming from the beam after passing through the target was observed with a Si(Li) x-ray detector. A collimator in front of the detector allowed detection of photons emitted in a 0.3-mm long region along the beam (the expected decay length at our beam energy is about 5 mm). The target was moved relative to the detector by means of a precision translator. The rate of decay from the 2^1S_0 state (normalized to the beam current) was measured as a function of foil-detector distance in order to determine the lifetime.

The photons emitted in the decay of the 2^1S_0 state form a continuous distribution up to the transition energy of about 8 keV. A major difficulty

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in the experiment comes from the presence of hydrogenlike Ni^{27+} in the beam. The $2S_{1/2}$ state of Ni^{27+} decays to the ground state by the emission of 2 E1 photons and since the transition energy is also near 8 keV these decays are indistinguishable from the decays from the heliumlike state. Repopulation by cascading, plus background counts from slit scattering must also be taken into account carefully.

At the present time we are in the process of completing the data analysis for our first run and it appears that a result at about the 3% level can be obtained from our existing data. For our next running of this experiment, we plan to improve our setup with the addition of a second Si(Li) detector and an improved collimation system designed to reduce background. With these improvements we expect to obtain a result with an uncertainty of better than 1%.

c. Measurement of the 1s Lamb Shift in One- and Two-electron Calcium
(R. W. Dunford, H. G. Berry, R. C. Pardo, M. L. A. Raphaelian, R. D. Deslattes*)

An experimental program has begun to measure the 1s lamb shift in one- and two-electron calcium ions. Such measurements are sensitive tests of Quantum Electrodynamics (QED) and Relativistic Quantum Mechanics. The QED corrections to the Dirac theory of one-electron ions exhibit characteristic dependences on $Z\alpha$, and there is considerable interest in exploring these dependences by measurement of the Lamb shift as a function of nuclear charge Z . There is also interest in measuring the Z -dependence of transition energies in He-like ions which are the simplest systems for which the electron-electron interaction must be considered.

Our experimental method for measurement of the Lamb shift utilizes precision X-ray spectroscopy and is based on the technique demonstrated by Deslattes, Schuch, and Justiniano who measured the 1s Lamb shift in Cl^{16+} using the accel/decel technique at the tandem-linac in Heidelberg. The ions were decelerated, stripped to bare nuclei, then slowed down and delivered to a gas target where they picked up electrons under single-collision conditions. The deceleration was required in order to obtain adequate cross sections for

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electron pickup in the gas target. The importance of using a gas target is that single-electron pickup is highly favored and so clean, symmetrical spectral lines, uncontaminated by spectator electrons are obtained.

As a first step in preparing for a measurement of the Lamb shift in hydrogen-like calcium ions we made some preliminary tests at ATLAS to develop the decelerated beams of Ca^{20+} and Ca^{19+} ions. In these tests, $^{40}\text{Ca}^{10+}$ ions were accelerated in the normal manner through the tandem accelerator and the "booster" stage of the linac. The ions were then stripped and either the $19+$, or the $20+$ charge state were magnetically selected and decelerated in the ATLAS section of the linac to energies of 105 and 129 MeV. The beams were delivered to a gas target where various pressures of He, Ne and Ar gases were used. A Si(Li) detector viewing the target monitored X-rays emitted at 90° to the beam axis (see Fig. IX-1). This test run demonstrated the capability of ATLAS for producing the decelerated beams needed for a measurement of the $1s$ Lamb shift in hydrogenlike or heliumlike calcium. It is expected that the results for deceleration of titanium ions will be similar giving an alternative possibility for Lamb-shift measurements at ATLAS. The next step in our program to test QED in high- Z systems will be to make a precision measurement of the $2p \rightarrow 1s$ transitions in heliumlike titanium. This will require the installation of a crystal spectrometer on the atomic physics beamline at ATLAS. A suitable spectrometer is being developed at NBS, Gaithersburg.

- d. State selective Electron Capture (R. W. Dunford, H. G. Berry, P. J. Billquist, R. C. Pardo, B. J. Zabransky, E. Bakke, K. O. Groeneveld, M. Hass, and M. L. A. Raphaelian)

We have begun a program at the ECR ion source to study state-selective electron capture using the technique of photon emission spectroscopy. Most of the existing data on electron capture in ion-atom collisions are measurements of total cross sections. There is little data on n distributions and even less on nl and $n\ell m$ distributions. Theoretical calculations determine $n\ell m$ distributions but these are normally averaged over to get total cross sections in order to compare with experiment. Recently, high-quality data have been obtained using ECR ion sources which determined the nl distributions in ion-atom collisions at low energy (<15 keV/amu). We have begun to extend these measurements to intermediate energy taking advantage of the 350-kV platform.

Fig. IX-1. A typical X-ray spectra for 105-MeV $^{40}\text{Ca}^{19+}$ incident on neon gas and 105-MeV $^{40}\text{Ca}^{20+}$ incident on helium gas.

In addition to their importance in extending tests of theoretical calculations to intermediate energy, measurements in this energy regime are useful to fusion research because collisions between plasma ions and neutral beams in tokamaks involve energies of 40 - 150 keV/amu. Photon emission following these collisions is used to measure impurity concentrations, study ion transport, and determine ion velocity distributions.

We have obtained data for a measurement of the cross sections for electron capture by O^{6+} incident on a He gas target (see Fig. IX-2). The target is a differentially-pumped gas cell which is viewed by a 2.2-meter grazing-incidence spectrometer. Cross sections have been obtained for six beam energies ranging from 72 keV up to 1.7 MeV. The lowest energy points overlap data taken by a group using the Groningen ECR ion source and are in reasonable agreement with their results. Our results show that the dominance of capture into the $n=3$ level continues at higher energy but that the relative importance of capture into $n=4$ increases with energy. We also see a marked increase in the relative population of the 3d level at higher energy.

The measurement of the cross sections for O^{6+} on He will be followed by measurements of $O^{6+,7+,8+}$, $C^{4+,5+,6+}$ and $Ne^{8+,9+,10+}$ on He, H_2 and H targets. The study of collisions between fully-stripped ions and atomic hydrogen is particularly important from a theoretical point of view. These experiments will require the development of a hydrogen beam target. We will also study the collisions of these ion species on alkali targets using the alkali beam being developed for the polarized target. Another particular interest is to search for and measure double-electron capture cross-sections to doubly-excited states.

Fig. IX-2. UV spectrum obtained from O^{6+} incident on helium gas. The lines correspond to transitions in lithium-like O^{5+} .

- e. Resonant Transfer and Excitation for Highly-charged Ions
 (K. H. Berkner,* E. M. Bernstein,† M. W. Clark,† W. G. Graham,#
 E. P. Kanter, D. Schneider,§ R. W. Dunford, and J. A. Tanist)

The overall goal of this research is to probe fundamental atomic interactions in ion-atom collisions by correlating projectile charge-changing events with x-ray emission. Experimentally, this work is carried out by measuring coincidences between x rays (emitted from the projectile and/or target) and the outgoing projectile charge state of interest.

Resonant transfer and excitation (RTE) occurs when capture of a bound target electron is accompanied by simultaneous excitation of the projectile followed by de-excitation via photon emission. This process is analogous to dielectronic recombination (DR) in which the captured electron is initially free instead of bound. This process is of fundamental interest in plasma physics. RTE and DR proceed via an inverse Auger transition and, hence, are resonant for projectile velocities (in the rest frame of the electron) corresponding to the allowed Auger electron energies. For both RTE and DR many intermediate-resonance states are possible, each one corresponding to an allowed Auger transition. Experimentally, observation of a resonant behavior in the x-ray yield associated with capture identifies the RTE mechanism. A formal theoretical treatment of simultaneous charge transfer and excitation in ion-atom collisions has been developed by Feagin, Briggs and Reeves. In our experiments at ATLAS, RTE was measured for Li-like Ni ions which is the heaviest system studied to date.

In the first run of this experiment at ATLAS we excited 550-MeV Ni^{25+} ions in a He gas cell and observed both K- and L-x-rays in coincidence with the charge-state-analyzed projectile ions. These experiments used a 2-dimensional position-sensitive low-pressure Breskin gas counter to detect the ions.

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Because of the high-count-rate capabilities of this detector we were able for the first time to study both the charge-changing and non-charge-changing components of the x-ray spectrum. This first run was set up in the large scattering chamber facility, while in a second run, the magnetic spectrograph in target Area III was used to analyze the charge states after capture. Additional runs of the experiment will be required in order to complete the RTE data for nickel.

X. ATOMIC PHYSICS USING A SYNCHROTRON LIGHT SOURCE

Construction of a new synchrotron storage ring - the Advanced Light Source (APS) - is scheduled to begin at Argonne in 1989, and will be ready for experiments in the mid-1990's. We are proposing to utilize the X-ray and extreme ultraviolet radiation from this source for studies in atomic physics.

We envision that the unsurpassed brightness of the APS will offer a vast array of possibilities for the atomic physics community. It is probable that some form of national group of atomic physics users of the APS will take form in the early 1990's. Before and during the construction of the APS facility, we shall be doing experiments at the National Synchrotron Light Source (NSLS) at Brookhaven, and have already initiated a collaboration with ongoing experiments there. The aim here is to develop some expertise at Argonne in ion trapping and other technologies related to atomic physics work at synchrotrons, with the idea in mind of establishing a fully fledged atomic physics program later at the APS.

Initial experiments include studies of multiple photoionization processes, followed by both trapping of multiply-charged ions, and by mass spectrometry of the multiply-charged ions. The trapped ions will also be used for secondary experiments such as electron excitation studies of highly-charged ions.

Atomic-physics studies of photoionization of heavy ions and atoms have recently been instigated by a group of researchers, principally from Texas A & M University (Professor David Church) and the University of Tennessee (Professor Ivan Sellin). Their initial work at the Stanford Synchrotron Radiation Laboratory resulted in the observations of highly-charged rare gas ions, for example Kr^{+9} , at very low recoil energies. This same group has now started experiments at the Brookhaven National Synchrotron Light Source (NSLS), in collaboration with a Brookhaven group (Dr. Keith Jones). We have arranged to participate in these experiments in the summer of 1988.

Since the recoil-ion energies correspond essentially to room temperatures or less, the work at NSLS is continuing with a program to trap the ions for subsequent secondary experiments. The Texas A & M group has previous experience in ion trap work, and has succeeded in trapping ions produced from

heavy-ion impact. The photoionizing technique will produce much cooler ions initially (the initial temperatures are at least two orders of magnitude smaller), thus allowing much cleaner trapping geometries, and the cooling of more ions to very low temperatures.

Initial experiments last year at the NSLS have succeeded in trapping rare gas ions in a Penning trap with a well depth of 250 mV. These measurements already give approximate results for charge-changing collisions for the heavy ions. Relaxation times of the different charge states can lead to rate coefficients and then to cross-sections, once the velocity distributions of the trapped ions have been determined.

Our collaboration with this group at the NSLS will involve initial experiments in the summer of 1988, using discretionary Argonne National Laboratory funding, as a first step toward an atomic physics program at the APS at Argonne. We expect that the group will become the basis for an atomic physics research team at the Argonne APS when it comes on-line.

In 1988 we have used Laboratory discretionary funds to collaborate on heavy-ion photoionization experiments using synchrotron radiation at the Brookhaven NSLS. This work involves measuring charge-changing collision rates of cool trapped ions.

FY 1989

We expect to build an improved heavy-ion trap to be used on-line at the Brookhaven NSLS. Our initial program will be to trap highly-charged rare gas ions - Ne^{8+} , Ar^{10+} and Xe^{10+} - then optimize cooling techniques, with a goal of producing very cold ions at very well-defined sets of velocities. These low-velocity ions will be used for several different types of experiments:

- 1) Study the production rates for the highest ion charge states which can be produced at the NSLS. The production rates depend on both single and multiple ionization cross sections for the heavy ions, and we expect these to be strongly wavelength dependent. This knowledge is essential for estimating the increase in charge-state production at the higher energy beams expected from the Argonne Advanced Photon Source (APS).

- 2) Sequential ionization by the synchrotron light beam, as part of a systematic study of photoionization cross sections in heavy ions.
- 3) Begin a study of ion-atom collision cross sections, including excitation and ionization, by studying the pressure dependence of the survival times of the ions in the ion trap.

This work will be part of the continuing collaboration with the Church-Sellin-Jones group. At the same time, we shall be studying the possible construction of a target facility at the Argonne Advanced Photon Source. We expect that Professor Church will spend part of his sabbatical leave at Argonne participating in these experiments.

Future Plans

FY 1990

We shall be continuing ion-trap and other experiments at the NSLS facility. We expect to begin a study of electron excitation and ionization cross sections using an electron beam/ion trap geometry. Some precision atomic structure experiments will become possible, provided that we can cool the trapped ions to a well-defined low temperature. Laser excitation from metastable or long-lived states will give useful tests of both fine and hyperfine structures, with little or no Doppler-broadening problems. Laser cooling to condensation temperatures for some ions may also become feasible. Also in 1990 we expect to begin formulating the design of a dedicated atomic physics beam line at the Argonne Advanced Photon Source.

XI. MOLECULAR STRUCTURES AND DYNAMICS FROM COULOMB-EXPLOSION MEASUREMENTS

Because of the roles of molecular ions and small clusters in combustion, catalysis, atmospheric chemistry, and plasma chemistry, an understanding of the structures and dynamics within charged molecules is of substantial interest in many areas of energy research. The major aim of the work described below is to initiate a systematic detailed study of the stereochemical structures and intramolecular dynamics of such molecules. The work will be performed principally in various collaborations with outside (non-ANL) members of the chemistry community who see the Coulomb-explosion technique and the associated unique ANL facilities as offering additional perspectives on many molecular ions and cluster ions of current scientific interest.

Tightly-collimated beams of molecular ions with energies variable in the range 0.5-4.5 MeV are directed onto thin (~30 Å) foil or gaseous targets. The distributions in laboratory velocities are measured with high resolution (~0.005° and ~600 psec) for the fragment ions. From the resultant set of completely correlated final velocity vectors of all the fragments, one can reconstruct the initial structure of the molecule at the moment of the Coulomb explosion. The recent development of the multiparticle MUPPATS detector has enabled us to measure directly the density distributions of atomic nuclei within small polyatomic molecules. These experiments provide a radically new source of information on the structures and vibrations of molecular ions.

Our previous experiments with several small polyatomic molecular ions and cluster ions have served as paradigms of the technique. As a result of this work, a new apparatus has been developed which will now permit us to study a much broader set of molecules than has hitherto been accessible. Additionally, these preliminary studies have afforded us the opportunity to develop new analysis methods for studying molecules with many degrees of freedom. The initiative outlined here seeks to exploit those developments with a new program beginning in 1990.

Following our early exploratory work, we have initiated several major improvements to the apparatus which will be completed this year. The principal development, the new Segmented Anode MUPPATS (SAM) detector, represents a significant enhancement in our detection capabilities which will permit us to address several interesting problems in molecular structure. The separation of particles onto two detectors (MUPPATS and SAM) will have the additional benefit of improving our efficiency for reconstruction of multiparticle events which presently drops off severely for more than 5 particles. Furthermore, the improved time resolution of the SAM detector is vital for accurate determinations of bond lengths between the slowly separating heavy-ion fragments.

One of the immediate aims of this work is to apply these techniques to several kinds of molecules for which traditional methods of spectroscopy and ab initio theory are inappropriate. Among these are the following classes:

- 1) Floppy Molecular ions: Molecular ions which exhibit large-amplitude coupled internal motions are particularly difficult for conventional approaches because of the breakdown of the local-mode approximations usually employed. Examples of these are non-classical molecules and of particular interest are highly-excited states contributing to unimolecular decomposition.
- 2) Inherently Diffuse Spectra: Ions whose emission spectra are inherently broad, such as butadiene, with line widths homogeneously broadened, leave little hope that such spectra can yield much structural information.
- 3) Exotic and Short-lived Species: Because of the difficulty in obtaining sufficient number densities, spectroscopic approaches are not applicable to the study of rare or highly reactive molecules. Of particular interest to our work are cluster ions and multiply-charged ions which are found in high-temperature plasmas.
- 4) Chirality: Coulomb-explosion images can be used to determine the absolute chiralities of small gas-phase structures.

The program described below investigates several molecules in these categories. Most of these studies will be collaborative with chemical physics groups outside Argonne.

The chemistry of hydrocarbon ions in the gas phase has been an active field of research in recent years not only because of the intrinsic interest in their properties but also because of their practical importance in the synthesis of interstellar molecules and in combustion. For example, such ions are known to be important in understanding the formation of soot in flames. As our preliminary studies have already indicated, positive hydrocarbon ions are particularly favorable for study by the Coulomb-explosion technique because of the ease of production and acceleration as well as the large charge/mass ratios obtainable for the fragment ions. For these reasons, a major thrust of our proposed research will be aimed at ions of the form $C_m H_n^{+q}$ ($m = 1-6$, $n = 0-6$, $q \geq 1$).

The Coulomb-explosion technique is especially valuable for molecules whose potential-energy surfaces exhibit several equivalent minima, or nearly degenerate minima, separated by very low barriers. In such cases, tunnelling motions are extremely rapid and the energy-level structure is very complex. The usual rigid-rotor harmonic-oscillator calculations of spectra are not even approximately valid. Methods involving full quantum-mechanical treatment of the spectroscopy of such systems are just now under development.

Prof. R. C. Woods (University of Wisconsin) has proposed to us that information from the Coulomb-explosion experiments can provide both initial guidance and critical tests of such theoretical analyses.

With the completion of the new detector system, one of our first goals will be to explore in greater depth the vibrational motions in $C_2H_3^+$. Our original work with this molecule was motivated by the considerable effort expended by spectroscopists in pursuit of the infrared spectrum. Because of the restricted solid angle of the MUPPATS detector, our previous experiments did not resolve the carbon charge states and thus were only sensitive to the mean geometry. As a result, we have been unable to put a very good experimental limit on the presence of the classical structure within our sample. That is, we were unable to distinguish between true geometrical changes as opposed to charge-state variations in those data. With the new apparatus this difficulty will be cleared up and we expect to establish firmly the true geometry. Furthermore, with charge-state-resolved data, we will have the geometries of each molecule in the sample and will thus be able to exploit our analysis techniques for deducing the vibrational motions of the nuclei. We also plan to explore the structural effects of deuteration by studying the species $C_2H_2D^+$ and $C_2D_2H^+$ as well.

In addition to this study of $C_2H_3^+$, we shall apply these new techniques to a variety of other molecules of the form $X_mH_n^+$. In particular, we plan to attack the problems of $C_2H_5^+$ and $H_5O_2^+$. Both of these molecules have been under investigation for quite some time by conventional spectroscopic approaches, as well as theory, but the results remain controversial. We are informed by Prof. R. S. Berry (University of Chicago) that the Coulomb-explosion approach can serve as an important tool in ultimately unraveling these problems.

Hydronium ion hydrates have been studied by physical chemists for many years, but the infrared spectra are often difficult to interpret. Such ions, which are abundant in the lower atmosphere, have been under intense investigation because of their connection to the problem of proton hydration and conduction in water. $H_5O_2^+$ is the simplest hydronium hydrate and yet, though the high-resolution infrared spectrum has been measured, these data remain unanalyzed. The structural information obtainable through Coulomb-explosion experiments will provide a new perspective that should help in understanding such complex spectra.

The ethyl-ion-molecule, $C_2H_5^+$, is another species almost ubiquitous in organic reaction systems which is far more amenable to the Coulomb-explosion technique than to spectroscopy, at least as far as its structure is concerned. Here, the central question to be answered is whether the structure is of the form CH_3CH_2 or CH_2-H-CH_2 .

Another primary focus of our program will be the study of rare, or exotic, molecules. These include neutral radicals, multiply-charged molecules, and atomic clusters. Structural information on short-lived or highly-reactive molecules is difficult to obtain experimentally although such species are important in both laboratory and astrophysical plasmas.

In collaboration with a group headed by Dr. W. L. Brown (AT&T Bell Labs), we plan to continue our study of carbon cluster ions at least through C_6^+ using methods similar to our earlier approach to C_3^+ . At the same time, we will also develop new ion sources to enable us to study other clusters as well. This information is important in understanding the roles of such clusters in catalysis where geometries play a crucial role in governing the breaking and rearranging of chemical bonds. In collaboration with the metal-cluster group headed by Dr. S. J. Riley in the Argonne Chemistry Division, we expect to develop an ion source that will produce aluminum cluster ions. We will be installing a vacuum pumping system in the high-voltage terminal of the Dynamitron, and this should permit us to use various techniques such as supersonic expansion and buffered trapping to allow these ions to internally cool before acceleration. The second major part of the cluster initiative will be the development of theoretical modeling tools which will sort out the ambiguities introduced into the Coulomb-explosion analysis by the presence of several identical heavy atoms all interacting simultaneously. In particular, quantum-mechanical approaches to the problem should resolve these difficulties. Our experience with C_3^+ suggests that it is now possible to treat such problems numerically using supercomputers. The application of these Coulomb-explosion techniques to the problem of cluster geometries represents a very exciting new development in this field which is of great interest to both the chemistry and materials science communities.

Prof. A. Moscovitz (University of Minnesota) has shown that the Coulomb-explosion method can be used to provide a new way to determine the absolute configurations of chiral molecules. This would be an important advance over

the only other known method, that of Bijvoet, which requires making a large, nearly perfect crystal of a molecule containing one atom much heavier than all of the rest in a known location. Moreover, the crystal in the Bijvoet method must withstand intense x-ray bombardment. Hence, the new method is expected to make possible the determination of absolute configurations of small chiral molecules, heretofore inaccessible. In order to demonstrate this method, we will begin this work by studying the configuration of $\text{CH}_3\text{CHDOH}^+$. This is a sufficiently small chiral molecule which should be possible to study with the existing apparatus.

Our experiments this year with $\text{C}_3\text{H}_3^{++}$ have demonstrated our ability to study multiply-charged molecules which are too rare, or short-lived, to be accessible to conventional spectroscopic techniques. In contrast, multiply-charged ions are significantly simpler for us to study because of the higher velocities obtained during acceleration in the Dynamitron. As a result, the dissociation fragments are more highly charged and the blurring effects of multiple scattering are markedly reduced, thereby significantly improving our bond-length resolutions compared to experiments with singly-charged species. Furthermore, because such molecules usually have only a single bound state, the problems of state-selectivity are eliminated. Prof. W. Klemperer (Harvard University) has pointed out to us that multiply-charged molecules are important constituents of laboratory plasmas and present difficulties in plasma diagnostics because of the lack of information on these species. We will begin this work with studies of several simple diatomics which have been extensively studied by theorists, including MgH^{++} and SiH^{++} . We also plan to search for CH_4^{++} which theory predicts to be planar, in contrast to the singly-charged species that we have already studied in detail.

We also plan to develop more tractable methods of mapping our Coulomb-explosion results from laboratory velocity-space to the multidimensional real-space of the exploding molecules. The procedures we have used so far are extremely time-consuming and expensive and have prevented us from mapping anything more than the mean geometries. As a result, although our analyses of the vibrational modes have demonstrated that there is a lot of rich information in the data, these studies have so far been limited to velocity space. We hope to perform such analyses in the future with the spatial coordinates.

Our present schemes of preparing the ions of most interest have obvious limitations. For the longer term, we need to be able to study molecules in carefully-prepared initial states of excitation. With this in view, we plan to study new sources of molecular ions appropriate for installation in the Dynamitron terminal. We have already begun to develop one such source specifically for this work. In order to use the new source in the HV terminal of the Dynamitron accelerator, extensive modifications will be required. In particular, this source, as well as several new innovative sources we are considering, present large gas loads to the accelerating tube of the Dynamitron and therefore require the installation of terminal-pumping capabilities, which we have begun. The new system will soon be operational. This feature will allow a much greater versatility in the molecular species that can be studied. We have also begun to study a variety of other sources (e.g. supersonic expansion, storage, liquid metal, etc.) which promise to provide vibrationally-cold, and a greater variety of, molecular ions. One, or more, of these sources will be adapted to the HV terminal of the Dynamitron during this period.

In collaboration with a group at Notre Dame University, we will begin a study of the prospects for producing fast beams of neutral radicals. In particular, we plan to study the neutral CH_5 radical by Coulomb-explosion techniques. Experiments with slower beams have demonstrated that metastable states of this radical exist with lifetimes in the 1-10 μsec range. These experiments have indicated that $\text{CH}_4 + \text{H}$ (rather than $\text{CH}_3 + \text{H}_2$) is the dominant dissociation pathway even for highly energized molecules. This suggests a D_{3h} structure for this radical rather than the calculated C_s geometry. It is hoped that Coulomb-explosion studies can resolve this discrepancy.

Another collaboration, to study fast neutrals, will be undertaken with Prof. R. G. Cooks (Purdue University). The motivation for this work is an improved understanding of ionic reaction mechanisms and their correlation with theory. There is thus a considerable interest in the mass spectrometry community in the structures of neutral fragments generated by dissociation of gas-phase ions. In particular, unimolecular decay of such molecular ions as aniline and pyridine will be studied to determine the structures of the fragment molecules.

We expect to extend our work gradually to the study of more complex molecular-ion structures at high regions of excitation. This will require some further development work to exploit different ion sources. In particular we plan to develop and build sources of selectively-excited molecular ions. We further plan to explore various schemes of pre-target excitation including gas cells, lasers and electron beams. The laser is attractive because of the selectivity afforded and is thus important to our long-range goal of studying the dynamics of nuclear motion in molecules in well-defined states of excitation.

Following the first stages of this work, we will begin to study the kinetics in the excited state of a molecule such as butadiene. By exciting the molecule at increasing distances (or times) from the stripping foil, one gives the molecule time for energy to dissipate and it may have time to find its way to the pathway for dissociation prior to Coulomb explosion.

As this work develops, it will become increasingly desirable to find alternative methods of accelerating high m/q molecular ions. The ion preparation stage has already become crucial in our work so far and is extremely difficult to deal with in the high-voltage terminal of a pressurized accelerator. We therefore plan to begin studies of alternative technologies which would allow ion preparation to take place externally. Such a development would permit studies of a far wider range of molecules (such as short-lived multicharged molecular ions and negatives) and allow us to more completely exploit the Coulomb-explosion technique.

This program will be strongly coupled to the new initiative in Chemical Dynamics in the Gas Phase in the Chemistry Division at ANL. We will utilize the ab initio calculations of Dr. T. H. Dunning et al. to determine the proper symmetry coordinates to explore in these molecules and the results of such analyses will be improved potential surfaces and transition-state geometries. The work on clusters focuses on species of relevance to the metal-cluster chemistry program of Dr. S. J. Riley et al. Several of the species to be studied will also be explored by the photoelectron/photoionization program of J. Berkowitz et al. The Coulomb-explosion program also interacts with related programs, external to Argonne, in chemical kinetics and combustion chemistry such as the programs of Drs. Y. T. Lee, R. J. Saykally, and H. F. Schaefer (Lawrence Berkeley Laboratory) and Dr. D. W. Chandler (Sandia Labs). Much of the proposed research will be

carried out in direct collaboration with the chemists named in this FWP. The collaborative work will involve brief visits (1-2 weeks) by the outside users for data collection followed by several months of data analysis carried out jointly here and at the home institutions.

OPERATION OF THE DYNAMITRON FACILITY

The Physics Division operates a high-current 5-MV Dynamitron accelerator which has unique capability as a source of ionized beams of most atoms and many molecules. Among the unusual facilities associated with the Dynamitron are (1) a beam line capable of providing "supercollimated" ion beams permitting angular measurements to accuracies of 0.005 degrees, (2) a beam-foil measurement system capable of measuring lifetimes down to a few tenths of a nanosecond, (3) a set-up for testing a polarized deuterium target for use in high-energy storage rings, (4) a variety of experimental apparatuses for weak-interaction studies, (5) a laser/ion-beam interaction beam line where laser beams from an argon pump and a dye laser are available coaxially and simultaneously with the Dynamitron ion beam, (6) a post-acceleration chopper system giving beam pulses of variable width from about one nanosecond to the millisecond range at repetition rates variable up to 8 MHz, (7) a scattering chamber for electron spectroscopy with electrostatic parallel-plate electron spectrometers with variable energy resolution (0.1% to 5%) and the capability to measure electron energies up to a few keV as a function of observation angle, and (8) two general-purpose beam lines used for a variety of short-term experiments. A VAX-11/750 computer system is available for on-line data analysis and for the control of experiments.

Future Developments at the Dynamitron (R. L. Amrein, H. G. Berry, E. P. Kanter, A. E. Ruthenberg, and B. J. Zabransky)

The Dynamitron will continue to be used primarily for accelerator-based atomic physics programs in the Physics Division. These include the work with fast molecular-ion beams and the atomic structure programs. Most of the planned developments are aimed at addressing specific problems for these research programs.

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 electron impact in the terminal. This was accomplished by modification of the electrode structure of a conventional duoplasmatron ion source. Several other schemes are under consideration for producing vibrationally cold molecular ions; however, many of these sources will present large gas loads on the accelerator tube. In order to accommodate such sources, we have begun the installation of a vacuum pumping system in the Dynamitron terminal consisting of a 300-l/s turbopump exhausted by a pump/compressor to a 10-l storage volume. An additional by-product of this system will be an external gas feed which will permit changing source gases without the necessity of opening the

accelerator tank. This new system will permit greater flexibility in the design of new ion sources. Further developments will also be required to instrument the terminal region to control the new sources.

A new research aim of the molecular-ion work has been the study of atomic clusters. As part of this work, a laser vaporization source will be constructed and installed in the Dynamitron to permit production of a wide variety of metallic and semiconductor clusters.

Our efforts will continue to improve the voltage stabilization of the terminal. The change of the recirculating fans has removed the last of the low-frequency sources. A new generating voltmeter is being constructed this year which will allow us to study the much lower high-frequency components of the ripple. This effort should make it feasible to perform several collinear laser/fast-beam experiments planned for the atomic structure program.

We also plan to pursue new sources of multicharged ions. A physicon ion source has been obtained for this purpose. With the completion of our test-bench facility, we plan to investigate the coupling of this new source to the accelerator tube to optimize beam currents and beam-velocity profiles. We hope to use this source to provide some multi-charged ion beams and possibly beams with high metastable-state populations.

Operational Experience of the Dynamitron (B. J. Zabransky, R. L. Amrein, and A. E. Ruthenberg)

Overall, the Dynamitron continued to perform well during the past year. It was shut down for a total of approximately 6 months spread over the year. During this time, the technical staff assisted in the construction of beam lines, small accelerators, ion sources, and machine modifications. The Dynamitron is now usually staffed 8 hours a day by two full-time staff, but can also be operated by experienced scientific personnel. This arrangement has proved to be effective. If the experiment requires it, the Dynamitron can continue to run through the night, manned only by the experimenters, or upon request, the Dynamitron can be staffed for two shifts a day. This is normally done with outside users or others not familiar with the operation of the accelerator.

During the year the accelerator was operated a total of 2175 hours. Of this time 1443 hours (66%) were scheduled for experimental research during which a beam was provided to the experimenters 77% of the time. Machine preparation time used up 22% of the scheduled research time and machine malfunctions 1%. Scheduled accelerator improvements (including the upgrading program) and modifications used a total of 732 hours or 34% of the total available time.

The great versatility of the Dynamitron continued to be exploited by the research staff. Ion currents on target varied from 1×10^{-17} amperes to 26 microamperes with terminal voltages ranging from 0.625 to 4.8 MV. A wide range of both atomic and molecular ions was delivered on target. They include: H^+ , $^2H^+$, $^3He^+$, C^+ , CH_3^+ , CH_4^+ , CH_5^+ , NH_3^+ , NH_4^+ , Al^+ , CO^+ , $C_2H_2D^+$, O_2^+ , C_3^+ , C_3H^+ , $C_3H_2^+$, $C_3H_3^+$, $C_3H_3^{2+}$, Ar^+ , Ar^{2+} , Xe^+ , Xe^{2+} , Xe^{7+}

A total of 38 investigators used the Dynamitron during 1987 in some phase of their experimental research. Of these, 22 were from the Physics Division, 8 were outside users from other research facilities, and two were members of the Resident Graduate Student Program. In addition, one graduate student and one undergraduate student participated in research at the Dynamitron. Of the scheduled time, 81% went to experiments involving members of the Physics Division. Outside users collaborated in experiments that used 58% of the total available time. Graduate students, undergraduate students, and participants in the Resident Graduate Student Program worked on experiments that used 23% of the time.

The Dynamitron itself has had only a few maintenance problems this year. The accelerating tube developed a leak at the first insulator just downstream of the ion source. This small pressure-sensitive leak has been sealed. Also, the Dynamitron could not reach full voltage on initial startup. The problem was traced to a faulty tube in the oscillator power supply that drives the Dynamitron. In addition, a ruptured flexible coupling on one of the three compressors that are used to pump the SF_6 insulating gas had to be replaced.

The high-voltage terminal of the Dynamitron has been improved by the addition of two liquid vials controlled by solenoid valves and a precision gas-metering valve actuated by a Selsyn drive motor. With this system the vapor above the liquid in either vial can be metered into the ion source where it is ionized by the plasma. The ions are then extracted, accelerated, and delivered to the experimental area. The addition of using liquids as a source of ions has

produced many new ions not previously available with gaseous sources and is now regularly used by many experiments.

An ion-source test-bench accelerator has been built during the last year and is now operating. It is a small 100-kV accelerator operated in air which will accept the ion sources normally used in the Dynamitron and includes magnetic mass analysis. The test bench allows us to test ion sources and adjust the source parameters to maximize the yield for ions of particular interest before the source is installed in the Dynamitron. Because of the long time needed to open and close the Dynamitron, changes to the ion source normally took at least a day. A large savings in manpower can now be realized by mounting the ion source on the test bench where changes can be made in a matter of minutes.

The Dynamitron cooling system has been rebuilt this year. The Dynamitron had been cooled by a freon compressor and air-condensing unit originally supplied with the machine. This old unit was prone to failure and had caused much down-time during the past several years. It had degraded to the point where major components which were obsolete needed to be replaced. A new water-to-water heat exchanger and temperature-control system located in the experimental area replaced the old freon unit. The new heat exchanger uses the building-supplied chilled water in the primary loop to cool the secondary loop of chemically-treated water that circulates through and cools the Dynamitron. The new system has worked flawlessly since its installation about six months ago.

Many problems plagued an old outside air-conditioning unit that maintained the temperature and humidity control for the Dynamitron data room, including the VAX-11/750 computer and data-acquisition system. This unit was replaced by a Liebert air-conditioning system located inside the data room. The Liebert unit is cooled by the building chilled water and will therefore be much more reliable than the old outside freon unit. The computer previously had to be shut down many times due to failure of the old unit, but there has been no down time since the new air-conditioning system was installed. Also, a chilled-water-cooled air-cooling unit was installed in the Dynamitron assembly area to replace a defective window air conditioner.

University Use of the Dynamitron (B. J. Zabransky)

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

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

During the year eight scientists came from six outside institutions to use the Dynamitron. They came from one state and four foreign countries. They participated in experiments that used 58% of the time scheduled for research. A list of those institutions from which outside users of the Dynamitron came during 1987 is given below. The list includes the name of the institution, the title of the research project, and the name of the principal investigators at each institution. The names of their Argonne collaborators (if any) are enclosed in parentheses.

- (1) University of Bochum, West Germany
Argon Beam Foil Spectroscopy
E. Trabert, S. Bliman,§ L. Curtis,* L. Engström,† R. Hutton,† I. Martinson,† (H. G. Berry, C. Kurtz, L. Young)
- (2) Centre d'Etudes Nucleaires, Grenoble, France
Argon Beam Foil Spectroscopy
S. Bliman, L. Curtis,* L. Engström,† R. Hutton,† I. Martinson,†, E. Trabert# (H. G. Berry, C. Kurtz, L. Young)
- (3) Kent State University, Kent, Ohio
Molecular-Ion-Induced Desorption Mass Spectroscopy
D. Fishel, (G. Hunt, M. Salehpour)

§Centre d'Etudes Nucleaires, Grenoble, France

*University of Toledo, Toledo, Ohio

†University of Lund, Lund, Sweden

- (4) University of Lund, Lund, Sweden
 Argon Beam Foil Spectroscopy
 L. Engström, R. Hutton, S. Bliman, § L. Curtis, * E. Trabert, #
 (H. G. Berry, C. Kurtz, L. Young)
 Aluminum Beam Foil Spectroscopy
 I. Martinson, L. Curtis, * (H. G. Berry, C. Kurtz, L. Young)
- (5) University of Toledo, Toledo, Ohio
 Aluminum and Argon Beam Foil Spectroscopy
 L. Curtis, S. Bliman, § L. Engström, † R. Hutton, † I. Martinson, †
 E. Trabert, # (H. G. Berry, C. Kurtz, L. Young)
- (6) Weizman Institute of Science, Israel¹
 The Geometrical Structure of C_3^+
 A. Faibis, (E. Bakke, E. Kanter, L. Tack, B. Zabransky)

§Centre d'Etudes Nucleaires, Grenoble, France

*University of Toledo, Toledo, Ohio

†University of Lund, Lund, Sweden

#University of Bochum, West Germany

The Resident Graduate Student Program is open to students who have finished their course work and passed their prelims. They come to Argonne and perform their Ph.D. thesis research here. Two members of this program worked at the Dynamitron during 1987. They participated in experiments that used 20% of the time allotted to research. Those who used the accelerator are listed below, together with their home university and their local thesis advisor.

- (1) J. Murduck, Northwestern University
 I. Shuller, advisor
- (2) M. Raphaelian, University of Illinois at Chicago
 H. G. Berry, advisor

In addition, the following graduate student and undergraduate student have participated in research based at the Dynamitron.

Graduate Student

- (1) R. Haar, University of Toledo
 H. G. Berry, advisor

Undergraduate Student

- (1) D. Clague, University of Birmingham
 R. Betts, advisor

STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the permanent staff of the Physics Division for the year ending 31 March 1988. 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 New York, Stony Brook, 1976
 §Bruce G. Glagola, Ph.D., University of Maryland, 1978
 ¶Michael Green, Ph.D., Indiana University, 1983
 Roy J. Holt, Ph.D., Yale University, 1972
 Harold E. Jackson, Jr., Ph.D., Cornell University, 1959
 Robert V. F. Janssens, Ph.D., Université 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
 *Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937
 *James D. Larson, Ph.D., California Institute of Technology, 1965
 *Frank J. Lynch, B.S., University of Chicago, 1944
 Thomas Moog, B.A., Princeton University, 1975
 James Napolitano, Ph.D., Stanford University, 1982

*Special Term Appointee.

†In charge of ATLAS operations and accelerator development.

‡Resident Associate Guest Appointee.

§ATLAS User Liaison Physicist.

¶Left the Physics Division in June 1987.

- Richard C. Pardo, Ph.D., University of Texas, 1976
 Karl Ernst Rehm, Ph.D., Technical University, Munich, 1973
 *G. Roy Ringo, Ph.D., University of Chicago, 1940
 Stephen J. Sanders, Ph.D., Yale University, 1977
 †John P. Schiffer, Ph.D., Yale University, 1954
 Kenneth W. Shepard, Ph.D., Stanford University, 1970
 #Silvia C. Tentindo Repond, Ph.D., University of Rome, 1979
 *George E. Thomas, B.A., Illinois Wesleyan, 1943
 Flemming Videbaek, Ph.D., University of Copenhagen, 1974
 Lester C. Welch, Ph.D., University of Southern California, 1970
 Bruce D. Wilkins, Ph.D., University of California, 1962
 *Jan L. Yntema, Ph.D., Free University of Amsterdam, 1952
 Benjamin Zeidman, Ph.D., Washington University, 1957

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

*Special Term Appointee.

†Associate Director of the Physics Division. Joint appointment with the University of Chicago.

#Joined the Physics Division in February 1987.

§Resident Associate Guest Appointee from the University of Illinois, Chicago, Illinois.

¶Resident Associate Guest Appointee.

**Special Term Appointee from University of Illinois, Urbana, Illinois.

ATOMIC AND MOLECULAR PHYSICS

- H. Gordon Berry, Ph.D., University of Wisconsin, 1967
 William J. Childs, Ph.D., University of Michigan, 1956
 Robert W. Dunford, Ph.D., University of Michigan, 1978
 *Donald S. Gemmell, Ph.D., Australian National University, 1960
 †Leonard S. Goodman, Ph.D., University of Chicago, 1952
 Elliot P. Kanter, Ph.D., Rutgers University, 1977
 ‡Gilbert J. Perlow, Ph.D., University of Chicago, 1940
 §Leslie Tack, Ph.D., University of Arizona, 1982
 ¶Zeev Vager, Ph.D. Weizmann Institute of Science, 1962
 Linda Young, Ph.D., University of California, Berkeley, 1981

ADMINISTRATIVE STAFF

- **Allan Bernstein, M.B.A., Rosary College, 1986
 ††James R. Specht, A.A.S., DeVry Technical Institute, 1964

TEMPORARY APPOINTMENTSPostdoctoral Appointees

- Christian Beck (from Centre National de la Recherche Scientifique, France):
 Nuclear physics research at ATLAS.
 (July 1985--June 1987)
- Ali Belkacem (from University of Lyon, France):
 Coulomb-explosion studies.
 (September 1987--)
- Chia-Rong Chen (from University of Iowa, Iowa City, Iowa):
 Nuclear theory studies.
 (September 1986--August 1987)

*Director of the Physics Division.

†Deceased October 1987.

‡Resident Associate Guest.

§Joined the Physics Division in September 1986. Term appointment to September 1987.

¶Joint appointment with Weizmann Institute of Science, Rehovot, Israel.

**Joined the Physics Division in April 1987.

††Assistant Director of the Physics Division.

- Ping-Lin Chung (from University of Iowa, Iowa City, Iowa):
Nuclear theory studies.
(October 1987--)
- Bronislaw K. Dichter (from Yale University, New Haven, Connecticut):
Experimental heavy-ion research.
(October 1985--September 1987)
- Ronald Gilman (from University of Pennsylvania, Philadelphia, Pennsylvania):
Medium-energy pion and electron experiments.
(August 1986--)
- Romain Holzmann (from University of Louvain, Belgium):
Gamma-ray spectroscopy of high-spin states at ATLAS.
(September 1984--August 1987)
- Jorg G. Keller (from University of Darmstadt, W. Germany):
Nuclear physics at ATLAS.
(October 1985--September 1987)
- Chia-jung Liu (from Yale University, New Haven, Connecticut):
Atomic physics at ATLAS.
(December 1987--)
- Wen Chao Ma (from Vanderbilt University, Nashville, Tennessee and Tsinghua University, Beijing, China):
Heavy ion nuclear physics research at ATLAS.
(January 1986--December 1987)
- Noura Mansour (from University of Virginia, Charlottesville, Virginia):
Accelerator-based atomic physics.
(May 1987--)
- Claude Marchand (from University of Paris, France):
Medium-energy studies. (September 1987--)
- Eugene Moore (from Florida State University, Tallahassee, Florida):
Heavy-ion physics at ATLAS.
(January 1988--)
- Charles Price (from Indiana University, Bloomington, Indiana):
Relativistic quantum-field theory.
(October 1986--)
- *Gabriele Rathke (from University of Mainz, W. Germany):
Heavy-ion research at ATLAS.
(July 1987--)

*Feodor Lynen Postdoctoral Fellowship from Alexander von Humboldt Foundation.

Amarjit Sen (from University of Western Ontario, Canada):
Laser-ion beam studies.
(June 1985--August 1987)

Tzu-Fang Wang (from Yale University, New Haven, Connecticut):
Heavy-ion research at ATLAS.
(February 1986--)

*Frank L. H. Wolfs (from University of Chicago, Chicago, Illinois):
(Heavy-ion research at ATLAS)
(June 1987--)

Long-Term Visitors (at Argonne more than 4 months)

†R. Stephen Berry (University of Chicago, Chicago, Illinois):
Atomic theory.
(October 1985--)

Christopher Bottcher (Oak Ridge National Laboratory, Oak Ridge, Tennessee):
Atomic theory.
(October 1986--September 1987)

#John W. Clark (Washington University, St. Louis, Mo.): Nuclear theory
studies.
(July--December 1987)

§Mark Drigert (University of Notre Dame, Notre Dame, Indiana): Heavy-ion
nuclear physics research at ATLAS.
(June 1986--June 1987)

Aurel Faibis (from Weizmann Institute of Science, Rehovoth, Israel):
Study of molecular ions and ion-beam target collisions.
(January 1987--July 1987)

Michael Hass (Weizmann Institute of Science, Rehovoth, Israel):
Molecular-ion studies; heavy-ion research at ATLAS.
(August 1987--)

Hans J. Körner (Technical University of Munich, W. Germany):
Heavy-ion research at ATLAS.
(August 1987--)

Harry J. Lipkin (Weizmann Institute of Science, Rehovot, Israel):
Investigation of current problems in hadron spectroscopy.
(June 1987--September 1987)

*Resident Graduate Student from September 1983 to May 1987.

†Joint appointment.

#Faculty Research Leave Appointee.

§Postdoctoral Appointee at Notre Dame University but resident at Argonne.

*Ralph E. Segel (Northwestern University, Evanston, Illinois): Pion absorption studies.
(August 1986--September 1987)

Resident Graduate Students

David T. Baran (Northwestern University, Evanston, Illinois): Medium-energy nuclear physics studies. (June 1985--)

Timothy Dinneen (University of Chicago, Chicago, Illinois): Laser spectroscopy of fast ions. (November 1986--)

Christopher Fasano (University of Chicago, Chicago, Illinois): Quark effects in nuclei. (October 1985--)

Michael A. Kroupa (University of Chicago, Chicago, Illinois): Search for magnetic monopoles using a plastic scintillator array.
(July 1982--)

Ross E. Mitchell (University of Chicago, Chicago, Illinois): Study of the stereochemical structure of small polyatomic molecular ions by the "Coulomb-expulsion" method.
(February 1988--)

Mark L. Raphaelian (University of Illinois at Chicago, Illinois): Accelerator-based atomic physics.
(January 1987--)

†Frank L. H. Wolfs (University of Chicago, Chicago, Illinois): Research in heavy-ion physics. (September 1983--May 1987)

Short-Term Visitors (at Argonne less than 4 months)

A. Faculty

Paul Barker (University of Auckland, New Zealand): Weak interactions physics. (February 1987)

Samuel L. Bliman (LaGrippe/D.R.F.G.): Heavy-ion research at ATLAS.
(August--September 1987)

Joachim Doehner (University of Heidelberg, W. Germany): Weak interactions. (July--August 1987)

Henry C. Griffin (University of Michigan, Ann Arbor, Michigan): Heavy-ion research at ATLAS.
(June--August 1987)

*Faculty Research Leave Appointee.

†Postdoctoral Appointee as of June 1987.

Karl-Ontjes Groeneveld (J. W. Goethe Universität, Frankfurt, W. Germany):
Atomic physics at ATLAS. (October--December 1987)

Edward L. Hohman (York Community High School, Elmhurst, Illinois):
Summer high-school student coordinator. (June--August 1987)

Akiro Iwamoto (JAERI, Tokyo, Japan): Nuclear theory studies.
(September--October 1987)

Mamady Kaba (Abidjan University, Ivory Coast, Africa): Heavy-ion
research at ATLAS. (June--August 1987)

*Bradley Keister (Carnegie-Mellon University, Pittsburgh, Pennsylvania):
Nuclear theory studies. (July--August 1987)

Akihiko Matsuyama (Shizuoka University, Japan): Nuclear theory studies.
(July--September 1987)

Gregory A. Natanson (Northwestern University, Evanston, Illinois):
Coulomb-explosion studies. (June--August 1987)

Michael Paul (Hebrew University, Jerusalem, Israel): Heavy-ion research
at ATLAS. (June--October 1987)

*Wayne Polyzou (University of Iowa, Iowa City, Iowa): Nuclear theory
studies. (May 1987)

*Francis Prosser (University of Kansas, Lawrence, Kansas):
Heavy-ion research at ATLAS.
(June--July 1987)

Bernard Schneck (Technical University of Munich, W. Germany): Heavy-ion
research at ATLAS. (July--September 1987)

*Timothy Steimle (Arizona State University, Tempe, Arizona): Atomic physics
studies. (June--July 1987)

Suehiro Takeuchi (JAERI, Tokyo, Japan): Heavy-ion research at ATLAS.
(September--October 1987)

*Michael Vineyard (University of Richmond, Virginia): Heavy-ion research
at ATLAS. (June--July 1987)

B. Graduate Students

David Clague (Birmingham University, England): Heavy-ion research
at ATLAS. (July--September 1987)

Juergen Last (University of Heidelberg, Germany): Weak interactions
studies. (June--July 1987)

Madhusree Mukerjee (University of Chicago, Chicago, Illinois): Heavy-ion research. (September 1987 --)

Thih-Yuen Tung (Northwestern University, Evanston, Illinois): Nuclear physics experiments. (September 1987--)

Zhou Yu (Northwestern University, Evanston, Illinois): Intermediate-energy physics. (September 1987--)

Undergraduate Students

Bryan Affolter (DeVry Institute of Technology, Lombard, Illinois): (February 1987--)

Jennifer Bauer (University of Richmond, Richmond, Virginia): (June--July 1987)

Daniel Bechtloff (Aurora University, Aurora, Illinois): (March--August 1987)

Margaret Becker (State University of New York, Binghamton, New York): (September--December 1987)

Robert Bleicher (North-Central College, Naperville, Illinois): (March--August 1987, January 1988)

William Boggs (Transylvania University, Lexington, Kentucky): (June--August 1987)

Jill Brossig (University of Illinois, Urbana, Illinois): (September 1987--January 1988)

Laura Budrik (Illinois Benedictine College, Lisle, Illinois): (March 1987--)

Daniel Burns (Lewis University, Lockport, Illinois): (March 1987--)

William Buttler (University of Texas, Austin, Texas): (January 1988--)

Stephen Caracci (University of Illinois, Urbana, Illinois.): (June--August, December 1987, January 1988)

Daniel J. Ciarlette (Lewis University, Lockport, Illinois): (October 1985--August 1987)

Thomas Coleman (College of St. Francis, Joliet, Illinois): (September 1985--July 1987)

Jay Dawson (Carnegie-Mellon University, Pittsburgh, Pennsylvania): (January 1988--)

- Stewart DeSoto (Wheaton College, Wheaton, Illinois):
(September 1987--)
- Joseph Dey (Washington University, St. Louis, Missouri):
(June--August 1987)
- James Done (Roosevelt University, Chicago, Illinois):
(January 1988--)
- John Douglass (Wheaton College, Wheaton, Illinois):
(June--August 1987)
- Douglas Dunston (Harvey Mudd College, Claremont, California):
(June--August 1987)
- Kristine Fowler (Carleton College, Northfield, Minnesota):
(June--August 1987)
- Karen Furer (University of Colorado, Boulder, Colorado):
(June--August 1987)
- Scooter Haase (E. New Mexico University, Portales, New Mexico):
(January 1988--)
- Jay Hartley (Williams College, Williamstown, Massachusetts):
(June--August 1987)
- Eric Johnson (Lewis University, Lockport, Illinois):
(January 1988--)
- Terence R. Jones (Institute of Technology, Ryswyk, The Netherlands):
January--April 1987)
- Marc Kaplanes (University of Illinois, Urbana, Illinois):
(June--August 1987)
- Michael Karls (University of Wisconsin, Milwaukee, Wisconsin):
(June--August 1987)
- Leslie Lin (Mass. Institute of Technology, Cambridge, Massachusetts):
(June--August 1987)
- Kenneth Luther (Mount Union College, Alliance, Ohio):
(January--April 1988)
- Timothy McCormick (DeVry Institute of Technology, Lombard, Illinois):
(March 1987--January 1988)
- Margaret McParland (Midwest College of Engineering/Illinois Institute of
Technology West, Glen Ellyn, Illinois):
(November 1985--December 1987)
- Sandra Monhardt (Lewis University, Lockport, Illinois):
(January 1986--June 1987)

Patrick Morton (North-Central College, Naperville, Illinois):
(April 1987--)

Gregory Perschbacher (College of St. Francis, Joliet, Illinois):
(February 1987--)

Bonnie Pewitt (University of Kentucky, Lexington, Kentucky):
(May--August 1987, January 1988)

Garry V. Queen (University of Illinois-Chicago Circle, Chicago, Illinois):
(October 1987--January 1988)

Carolyn Robins (Lewis University, Lockport, Illinois):
(June--August 1987)

Loren St. Clair (Kalamazoo College, Kalamazoo, Michigan):
(September 1987--April 1988)

Brian Silverstein (University of Illinois, Urbana, Illinois):
(June--August 1987)

George Thiruvathakal (Lewis University, Lockport, Illinois):
(May--December 1987)

Steven Vavrik (University of Illinois, Urbana, Illinois):
(June--August 1987)

Richard Vondrasek (University of Chicago, Chicago, Illinois):
(June 1987--)

Michael J. Wolff (Marquette University, Milwaukee, Wisconsin):
(June--August 1987)

Diane Williamson (University of Illinois-Chicago Circle, Chicago, Illinois):
(June--December 1987)

Stefan Zemsch (Technische Universität München, W. Germany):
(January 1987--)

PRE-COLLEGE PROGRAM (Just Graduated from High School)
(June--August 1987)

Rhonda Berg (Argo High School)
James Debardelaben (Mendel Catholic High School)
Kevin Florey (Notre Dame High School)
Rebecca Goodman (Glenbard North High School)
Paul Stefanski (Riverside/Brookfield High School)

HIGH SCHOOL STUDENT AIDES
(June--July 1987)

Bruce Berger (Downers Grove South High School)
Glen Lew (York Community High School)
Peter Pashigian (University of Chicago High School)
Stephen Pecis (Lyons Township High School)
Jason Stott (Lyons Township High School)

TECHNICAL AND ENGINEERING STAFF

*Eric L. Bakke
 Ralph Benaroya
 Peter J. Billquist
 John M. Bogaty
 †Patric K. Den Hartog
 Joseph Falout
 Jack T. Goral
 ‡John P. Greene
 Ray E. Harden
 Dale J. Henderson
 Donald V. Hulet
 James M. Joswick
 Raymond B. Kickert
 §Gary W. Klimczak
 Robert Kowalczyk
 Charles A. Kurtz
 Paul Markovich
 Floyd H. Munson, Jr.
 Bruce G. Nardi
 James E. Nelson
 ¶Iain R. Tilbrook
 #Philip R. Wilt
 **Bruce J. Zabransky
 Gary P. Zinkann

*Joined the Physics Division in September 1986 for a period of two years.

†Supervisor of tandem-superconducting linac operations.

‡Joined the Physics Division in October 1987.

§Left the Physics Division in October 1987.

¶Joined the Physics Division in August 1987.

#Joined the Physics Division in January 1988.

**In charge of Dynamitron accelerator operations.

PUBLICATIONS FROM 1 APRIL 1987 THROUGH 31 MARCH 1988

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.

JOURNAL ARTICLES AND BOOK CHAPTERS

ELECTRON-CAPTURE BRANCHING RATIO OF $^{81}\text{Kr}^m$

Cary N. Davids, T. F. Wang, I. Ahmad, R. Holzmann, and R. V. F. Janssens
Phys. Rev. C 35, 1114 (1987)

SUBBARRIER NUCLEON TRANSFER: DOORWAY TO HEAVY-ION FUSION

W. Henning, F. L. H. Wolfs, J. P. Schiffer, and K. E. Rehm
Phys. Rev. Lett. 58, 318 (1987)

PERFORMANCE OF A LARGE BRAGG-CURVE SPECTROMETER

M. F. Vineyard, B. D. Wilkins, D. J. Henderson, D. G. Kovar, C. Beck,
C. N. Davids, and J. J. Kolata
Nucl. Instrum. Methods A255, 507 (1987)

SEARCH FOR SHAPE ISOMERS IN ^{56}Ni

B. K. Dichter, P. D. Parker, S. J. Sanders, R. R. Betts, and S. Saini
Phys. Rev. C 35, 1304 (1987)

SINGLE PARTICLE RADIATION BETWEEN HIGH SPIN STATES IN ^{147}Gd

J. Borggreen, G. Sletten, S. Bjornholm, J. Pedersen, A. Del Zoppo,
D. C. Radford, R. V. F. Janssens, P. Chowdhury, H. Emling, D. Frekers and
T. L. Khoo
Nucl. Phys. A466, 371 (1987)

^{41}Ca CONCENTRATION IN TERRESTRIAL MATERIALS AND ITS PROSPECTS FOR DATING OF
PLEISTOCENE SAMPLES

W. Henning, W. A. Bell, P. J. Billquist, B. Glagola, W. Kutschera, Z. Liu,
H. F. Lucas, M. Paul, K. E. Rehm and J. L. Yntema
Science 236, 725 (1987)

SHAPE COEXISTENCE, EVOLUTION AND THE PARALLEL PROTON-NEUTRON CORE BREAKING IN
 $^{155}\text{Er}_{87}$ STUDIED WITH THE HELP OF THE BaF_2 4π -DETECTION SYSTEM

F. A. Beck, T. Byrski, S. Rouabah, D. Curien, N. Bendjaballah, C. Costa,
C. Gehringer, B. Haas, J. C. Merdinger, J. P. Vivien, G. Bastin, C.
Schück, D. Frekers, R. V. F. Janssens, T. L. Khoo, W. Kühn, J. Dudek, F.
Menas and W. Nazarewicz
Phys. Lett. B192, 49 (1987)

FISSION AND QUASIFISSION IN U-INDUCED REACTIONS

W. Q. Shen, J. Albinski, A. Gobbi, S. Gralla, K. D. Hildenbrand, H.
Herrman, J. Kuzminski, W. F. J. Muller, H. Stelzer, J. Toke, B. B. Back,
S. Bjornholm, S. P. Sorensen
Phys. Rev. C 36, 115 (1987)

A PRESCRIPTION FOR THE REMOVAL OF COMPTON-SCATTERED GAMMA RAYS FROM GAMMA-RAY SPECTRA

D. C. Radford, I. Ahmad, R. Holzmann, R. V. F. Janssens and T. L. Khoo
Nucl. Instrum. Methods A258, 111 (1987)

ANISOTROPIES IN TRANSFER-INDUCED FISSION OF $^{16}\text{O} + ^{232}\text{Th}$

F. Videbaek, S. G. Steadman, G. G. Batrouni and J. Karp
Phys. Rev. C 35, 2333 (1987)

LEVEL STRUCTURE OF ^{148}Gd UP TO $I = 44$

M. Piiparinen, M. W. Drigert, R. V. F. Janssens, I. Ahmad, J. Borggreen,
R. R. Chasman, P. J. Daly, B. K. Dichter, H. Emling, U. Garg, Z. W.
Grabowski, R. Holzmann, T. L. Khoo, W. C. Ma, M. Quader, D. C. Radford,
and W. Trzaska
Phys. Lett. B 194, 468 (1987)

SYSTEMATICS OF QUASI-ELASTIC NEUTRON TRANSFER CROSS SECTIONS FOR HEAVY-ION INDUCED REACTIONS

A. M. Van Den Berg, K. E. Rehm, D. G. Kovar, W. Kutschera, and G. S. F.
Stephans
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EVOLUTION OF NUCLEAR STRUCTURE WITH INCREASING SPIN AND INTERNAL EXCITATION ENERGY IN ^{152}Dy

R. Holzmann, I. Ahmad, B. K. Dichter, H. Emling, R. V. F. Janssens, T. L.
Khoo, W. C. Ma, M. W. Drigert, U. Garg, D. C. Radford, P. J. Daly,
Z. Grabowski, H. Helppi, M. Quader and W. Trzaska
Phys. Lett. B 195, 321 (1987)

A NEW METHOD FOR MEASURING THE NEUTRON-INDUCED BACKGROUND IN BGO COMPTON-SUPPRESSED Ge DETECTORS APPLIED TO IN-BEAM γ -RAY STUDIES

R. Holzmann, I. Ahmad, R. V. F. Janssens, T. L. Khoo, D. C. Radford, M. W.
Drigert, and U. Garg
Nucl. Instrum. Methods A260, 153 (1987)

HIGH SENSITIVITY ALPHA-PARTICLE AND ELECTRON SPECTROSCOPY

Irshad Ahmad
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MEASUREMENT OF SUBBARRIER TRANSFER REACTIONS FOR $^{58}\text{Ni} + \text{Sn}$ USING A RECOIL MASS SEPARATOR

R. R. Betts, P. M. Evans, C. N. Pass, N. Poffe, A. E. Smith, L. Stuttge,
J. S. Lilley, D. W. Baney, K. A. Connell, J. Simpson, J. R. H. Smith,
A. N. James, and B. R. Fulton
Phys. Rev. Lett. 59, 978 (1987)

DISTRIBUTION OF REACTION STRENGTH IN $^{32}\text{S} + ^{182}\text{W}$ COLLISIONS

J. G. Keller, B. B. Back, B. G. Glagola, D. Henderson, S. B. Kaufman, S.
J. Sanders, R. H. Siemssen, F. Videbaek, B. D. Wilkins, and A. Worsham
Phys. Rev. C 36, 1364 (1987)

STRENGTH OF DEEP-INELASTIC SCATTERING FOR $^{58}\text{Ni} + ^{124}\text{Sn}$ AT SUB-BARRIER ENERGIES
F. L. H. Wolfs, W. Henning, K. E. Rehm, and J. P. Schiffer
Phys. Lett. B196, 113 (1987)

VELOCITY AND ANGULAR DISTRIBUTIONS OF EVAPORATION RESIDUES FROM ^{32}S -INDUCED REACTIONS

J. D. Hinnefeld, J. J. Kolata, D. J. Henderson, R. V. F. Janssens, D. G. Kovar, K. T. Lesko, G. Rosner, G. S. F. Stephans, A. M. van den Berg, B. D. Wilkins, F. W. Prosser, S. V. Reinert, and P. L. Gonthier
Phys. Rev. C 36, 989 (1987)

LEVEL STRUCTURE OF $^{149}_{68}\text{Er}_{81}$ AND HIGH-SPIN ISOMERISM IN PROTON-RICH $N=81, 82, 83$ NUCLEI

R. Broda, P. J. Daly, J. McNeill, R. V. F. Janssens, and D. C. Radford
Z. Phys. A - Atomic Nuclei 327, 403 (1987)

TESTS OF LARGE AIR-CORE SUPERCONDUCTING-SOLENOID AS A NUCLEAR REACTION-PRODUCT SPECTROMETER

R. L. Stern, F. D. Becchetti, T. Casey, J. W. Janecke, P. M. Lister, W. Z. Liu, D. G. Kovar, R. V. F. Janssens, M. F. Vineyard, W. R. Phillips, and J. J. Kolata
Rev. Sci. Instr. 58, 1682 (1987)

LEVEL STRUCTURE OF ^{225}Ac

I. Ahmad, J. E. Gindler, A. M. Friedman, R. R. Chasman and T. Ishii
Nucl. Phys. A472, 285 (1987)

SEARCH FOR SHARP LINES IN $e^+ - e^-$ COINCIDENCES FROM POSITRONS ON Th

T. F. Wang, I. Ahmad, S. J. Freedman, R. V. F. Janssens, and J. P. Schiffer
Phys. Rev. C 36, 2136 (1987)

FISSION AND DEEP-INELASTIC SCATTERING YIELDS FOR $^{58}\text{Ni} + ^{112,124}\text{Sn}$ AT ENERGIES AROUND THE BARRIER

F. L. H. Wolfs
Phys. Rev. C 36, 1379 (1987)

ASYMMETRIC FISSION OF ^{56}Ni

S. J. Sanders, D. G. Kovar, B. B. Back, C. Beck, B. K. Dichter, D. Henderson, R. V. F. Janssens, J. G. Keller, S. Kaufman, T.-F. Wang, B. Wilkins, and F. Videbaek
Phys. Rev. Lett. 59, 2856 (1987)

AVERAGE SPINS OF PRIMARY FISSION FRAGMENTS

Y. Abdelrahman, J. L. Durrell, W. Gelletly, W. R. Phillips, I. Ahmad, R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, and M. W. Drigert
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MEASUREMENT OF THE NUCLEAR LEVEL DENSITY AT HIGH SPINS

S. Henss, A. Ruckelshausen, R. D. Fischer, W. Kühn, V. Metag, R. Novotny, R. V. F. Janssens, T. L. Khoo, D. Habs, D. Schwalm, D. Freeman, G. Duchene, B. Haas, F. Haas, S. Hlavac, and R. S. Simon
Phys. Rev. Lett. 60, 11 (1988)

INTRINSIC REFLECTION ASYMMETRY IN ^{225}Ra : ADDITIONAL INFORMATION FROM A STUDY OF THE α -DECAY SCHEME OF ^{229}Th

R. G. Helmer, M. A. Lee, C. W. Reich, and I. Ahmad
Nucl. Phys. A474, 77 (1987)

THE DESIGN AND PERFORMANCE OF THE PARALLEL MULTIPROCESSOR NUCLEAR PHYSICS DATA-ACQUISITION SYSTEM, DAPHNE

L. C. Welch, T. H. Moog, R. T. Daly and F. Videbaek
IEEE Trans. Nucl. Sci. NS-34, 822-825 (1987)

LEVEL STRUCTURE OF $^{149}_{68}\text{Er}_{81}$ AND HIGH-SPIN ISOMERISM IN PROTON-RICH $N = 81, 82, 83$ NUCLEI

R. Broda, P. J. Daly, J. McNeill, R. V. F. Janssens, and D. C. Radford
Z. Phys. A - Atomic Nuclei 327, 403 (1987)

EVIDENCE FOR SUPERDEFORMATION IN ^{148}Gd

M. W. Drigert, R. V. F. Janssens, R. Holzmann, R. R. Chasman, I. Ahmad, J. Borggreen, P. J. Daly, B. K. Dichter, H. Emling, U. Garg, Z. W. Grabowski, T. L. Khoo, W. C. Ma, M. Piiparinen, M. Quader, D. C. Radford and W. Trzaska
Phys. Lett. B201, 223 (1988)

$^{48}\text{Ti} + ^{104}\text{Ru}$ SINGLE-NUCLEON TRANSFER AT THE BARRIER

S. J. Sanders, B. B. Back, R. R. Betts, D. Henderson, R. V. F. Janssens, K. E. Rehm, and F. Videbaek
Phys. Rev. C 37, 1318 (1988)

QUASI-ELASTIC PROCESSES IN ^{58}Ni - and ^{64}Ni -INDUCED REACTIONS ON Sn ISOTOPES

A. M. van den Berg, W. Henning, L. L. Lee, K. T. Lesko, K. E. Rehm, J. P. Schiffer, G. S. F. Stephans, F. L. H. Wolfs, and W. S. Freeman
Phys. Rev. C 37, 178 (1988)

SUPERCONDUCTING LINEAR ACCELERATORS FOR HEAVY IONS

Lowell M. Bollinger
Ann. Rev. Nucl. Part. Sci. 36, 475 (1987)

MEASUREMENTS OF RELATIVE ANGULAR DISTRIBUTIONS FOR THE $^2\text{H}(\gamma, n)\text{H}$ REACTION BELOW 18 MeV

K. E. Stephenson, R. J. Holt, R. D. McKeown, and J. R. Specht
Phys. Rev. C 35 2023 (1987)

BETA AND NEUTRINO SPECTRA IN THE DECAY OF ^8B

J. Napolitano, S. J. Freedman, and J. Camp
Phys. Rev. C 36, 298 (1987)

MEASUREMENT OF ENERGY EMISSION FROM O+A AND p+A COLLISIONS AT 14.5 GEV/C PER NUCLEON WITH A LEAD-GLASS ARRAY

T. Abbott, Y. Akiba, D. Alburger, D. Beavis, R. R. Betts, M. A. Bloomer, P. D. Bond, C. Chasman, Y. Y. Chu, B. A. Cole, J. B. Costales, H. Crawford, J. B. Cumming, R. Debbe, E. Duek, H. A. Enge, J. Engelage, S. Y. Fung, D. Greiner, L. Grodzins, S. Gushue, H. Hamagaki, O. Hansen, P. Haustein, S. Hayashi, S. Homma, H. N. Huang, Y. Ikeda, S. Katcoff, S. Kaufman, R. J. Ledoux, M. J. LeVine, P. Lindstrom, M. A. J. Mariscotti, Y. Miake, R. Morse, S. Nagamiya, J. Olness, C. Parsons, L. P. Remsberg, M. Sarabura, A. Shor, S. G. Steadman, G. S. F. Stephans, T. Sugitate, A. W. Sunyar, M. Tanaka, M. J. Tannenbaum, M. Torikoshi, J. H. Van Dijk, F. Videbaek, P. Vincent, E. Vulgaris, V. Vutsadakis, W. A. Watson III, H. E. Wegner, D. S. Woodruff and W. Zajc
Phys. Lett. B197, 285 (1987)

DISTRIBUTED DATA ACQUISITION FOR BNL802 I: THE FRONT END

M. J. LeVine, W. A. Watson III, Hans von der Schmitt, and Sheldon Kaufman
IEEE Trans. Nucl. Sci. NS-34, 830 (1987)

THE TRIGGER SUPERVISOR: MANAGING TRIGGERING CONDITIONS IN A HIGH-ENERGY PHYSICS EXPERIMENT

Bernard Wadsworth, Richard Lanza, M. J. LeVine, R. A. Scheetz, and Flemming Videbaek
IEEE Trans. Nucl. Sci. NS-34, 980 (1987)

HIGH MOMENTUM COMPONENTS IN NUCLEI

M. Avan, A. Baldit, J. Castor, M. El Zoubidi, J. Fargeix, H. Fonvieille, P. Force, J. L. Guelou, B. Harradi, G. Landaud, J. P. Didelez, F. Reide, M. Berhneim, A. Gerard, A. Magnon, C. Marchand, J. Morgenstern, J. Picard, P. Vernin, and H. Jackson
Phys. Rev. C 37, 231 (1988)

DOUBLE CHARGE EXCHANGE TO THE DOUBLE ISOBARIC ANALOG STATE AT $T_{\pi} \sim 292$ MeV

J. D. Zumbro, H. T. Fortune, M. Burlein, C. L. Morris, Z.-F. Wang, R. Gilman, Kalvir S. Dhuga, G. R. Burleson, M. W. Rawool, R. W. Garnett, M. J. Smithson, D. S. Oakley, S. Mordechai, C. Fred Moore, M. A. Machuca, D. L. Watson and N. Auerbach
Phys. Rev. C 36, 1479 (1987)

MEASUREMENT OF HIGH MOMENTUM TRANSFER REACTIONS BY RECOIL DETECTION

J. Homolka, W. Schott, W. Wagner, W. Wilhelm, R. D. Bent, M. Fatyga, R. E. Pollock, M. Saber, R. E. Segel, P. Kienle, and K. E. Rehm
Nucl. Instrum. Methods A260, 418 (1987)

THE BETA-DECAY ASYMMETRY OF THE NEUTRON

E. Klempt, P. Bopp, L. Hornig, J. Last, S. J. Freedman, D. Dubbers, and O. Scharpf
Z. Phys. C 37, 179 (1988)

BOUND-NUCLEON RESPONSE FUNCTIONS FROM THE REACTION $^{40}\text{Ca}(e,e'p)^{39}\text{K}^*$ AND
NUCLEAR-MEDIUM EFFECTS

D. Reffay-Pikeroen, M. Bernheim, S. Boffi, G. P. Capitani, E. de Sanctis,
S. Frullani, F. Garibaldi, A. Gerard, C. Giusti, H. Jackson, A. Magnon, C.
Marchand, J. Mougey, J. Morgenstern, F. E. Pacati, J. Picard, S. Turck-
Chieze, and P. Vernin

Phys. Rev. Lett. 60, 776 (1988)

COUPLED-CHANNELS ANALYSIS OF SILICON-NICKEL FUSION REACTIONS

S. Landowne, Steven C. Pieper, and F. Videbaek

Phys. Rev. C 35, 597 (1987)

$\Lambda\Lambda$ HYPERNUCLEI AND THE $\Lambda\Lambda$ INTERACTION

A. R. Bodmer and Q. N. Usmani

Nucl. Phys. A463, 221 (1987)

SUPERDEFORMATION IN THE RARE-EARTH REGION

R. R. Chasman

Phys. Lett. B 187, 219 (1987)

HIGHER-ORDER COUPLING EFFECTS IN LOW ENERGY HEAVY-ION FUSION REACTIONS

H. Esbensen and S. Landowne

Phys. Rev. C 35, 2090 (1987)

NUCLEAR STRUCTURE DEPENDENCE OF THE (p,π^+) REACTION

Dieter Kurath

Phys. Rev. C 35, 2247 (1987)

S AND P WAVE η PRODUCTION IN AN SU(3) BAG MODEL

John A. Johnstone

Phys. Lett. B189, 215 (1987)

SPIN DISTRIBUTIONS IN HEAVY-ION FUSION REACTIONS

H. Esbensen and S. Landowne

Nucl. Phys. A467, 136 (1987)

THE (p,n) REACTION AND THE NUCLEON-NUCLEON FORCE

G. F. Bertsch and H. Esbensen

Rep. Prog. Phys. 50, 607 (1987)

THE α -CLUSTER HYPERNUCLEI $^5_\Lambda\text{He}$, $^6_\Lambda\text{He}$, $^9_\Lambda\text{Be}$, $^{10}_\Lambda\text{Be}$ AND HYPERNUCLEAR INTERACTIONS

A. R. Bodmer and Q. N. Usmani

Nucl. Phys. A468, 653 (1987)

CCFUS - A SIMPLIFIED COUPLED-CHANNEL CODE FOR CALCULATION OF FUSION CROSS
SECTIONS IN HEAVY-ION REACTIONS

C. H. Dasso and S. Landowne

Comp. Phys. Comm. 46, 187 (1987)

COMMENT ON "REDUCTION OF COUPLED EQUATIONS FOR HEAVY ION REACTIONS"

H. Esbensen, S. Landowne, and C. Price

Phys. Rev. C 36, 1216 (1987)

- PAIR-TRANSFER WITH HEAVY DEFORMED NUCLEI AT HIGH SPINS
C. Price, H. Esbensen and S. Landowne
Phys. Lett. B 195, 524 (1987)
- SEARCHING FOR THE BERRY PHASE EFFECT WITH TWO-PARTICLE TRANSFER REACTIONS
C. Price, H. Esbensen and S. Landowne
Phys. Lett. B 197, 15 (1987)
- UNITARY MESON-EXCHANGE π NN MODELS: NN AND π d ELASTIC SCATTERING
T.-S. H. Lee and A. Matsuyama
Phys. Rev. C 36, 1459 (1987)
- ENHANCEMENT OF THE RELATIVE $\Delta S=1/\Delta S=0$ RESPONSE OF ^{40}Ca AT HIGH EXCITATION ENERGIES
C. Glashausser, K. Jones, F. T. Baker, L. Bimbot, H. Esbensen, R. W. Ferguson, A. Green, S. Nanda, and R. D. Smith
Phys. Rev. Lett. 58, 2404 (1987)
- HIGH-SPIN EXCITATION IN THE ROTATING FRAME AND SUDDEN APPROXIMATIONS
H. Esbensen, S. Landowne and C. Price
Phys. Rev. C 36, 2359 (1987)
- STRUCTURE FUNCTIONS AND CORRELATIONS IN NUCLEI
R. Schiavilla, D. S. Lewart, V. R. Pandharipande, Steven C. Pieper, R. B. Wiringa, and S. Fantoni
Nucl. Phys. A473, 267 (1987)
- QUARK COMPOUND BAG MODEL FOR NN SCATTERING UP TO 1 GeV
C. Fasano and T.-S. H. Lee
Phys. Rev. C 36, 1906 (1987)
- NUCLEAR EFFECTS IN DEEP INELASTIC LEPTON SCATTERING
E. L. Berger and F. Coester
Ann. Rev. Nucl. Part. Sci. 37, 463 (1987)
- SYSTEMATICS OF LIGHT DEFORMED NUCLEI IN RELATIVISTIC MEAN-FIELD MODELS
R. J. Furnstahl, C. E. Price, and G. E. Walker
Phys. Rev. C 36, 2590 (1987)
- UNITARY MESON-EXCHANGE CALCULATION OF NN + NN π REACTION
A. Matsuyama and T.-S. H. Lee
Phys. Rev. C 34, 1900 (1986)
- HYPERFINE STRUCTURE OF $^{151,153}\text{Eu}^+$ IN THE STATE $4f^7(^8\text{S}^o)5d\ ^9\text{D}_4^o$ BY COLLINEAR LASER-RF DOUBLE RESONANCE
A. Sen, L. S. Goodman, W. J. Childs, and C. Kurtz
Phys. Rev. A 35, 3145 (1987)
- HYPERFINE STRUCTURE OF METASTABLE LEVELS IN $^{151,153}\text{Eu}^+$ BY COLLINEAR LASER-RF DOUBLE RESONANCE SPECTROSCOPY
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