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FOREWORD

This past year has brought about several important developments for the ANL Physics Division. The new superconducting positive-ion injector (PII) for ATLAS has been completed and commissioned successfully. Just recently a uranium beam of excellent quality was accelerated to 5.7 MeV/u. The various activities from the aftermath of the Tiger Team visit have been completed and the research program at ATLAS has fully resumed under improved conditions and ~200 scientists and students participated in research at ATLAS during the year. Activities in Medium-Energy Physics aimed at an experimental program at CEBAF have accelerated with the construction of the SOS spectrometer and the approval of several additional ANL experiments for the first phase of CEBAF operation. The atomic physics initiative towards a program at the Argonne Advanced Photon Source (APS) has been formulated and first experiments using the NSLS at Brookhaven, aimed at the additional development of the future program at the APS, have begun.

The new superconducting positive-ion injector (PII) for ATLAS was completed and tested successfully for the first time during March by accelerating a beam of $^{40}$Ar$^{11+}$. The success of this test constitutes final proof of the technical soundness of this novel accelerator concept based on acceleration from very low velocities by independently-phased superconducting resonators. Earlier this summer a $^{208}$Pb beam and somewhat later a $^{238}$U beam were also accelerated.

The heavy-ion program is moving into unexplored directions based on new capabilities and on the completion of major new experimental apparatus. The Fragment Mass Analyzer (FMA) is in full operation, showing a mass resolution of up to 1 part in 550 and excellent beam suppression capability for inverse reactions.

The main components of APEX, the ATLAS Positron Experiment, have been installed and are presently being tested. This experiment studies the yet unexplained peaks found at GSI in electron-positron coincidences for collisions between two very heavy nuclei. It is a joint effort of six university groups and Argonne. With the uranium beams now available, first beam tests are scheduled for September.

A major part of the research effort in the past year was devoted to gamma-ray experiments. The focus of this work has been on the study of superdeformation, especially in the mass-190 region which was discovered at ATLAS three years ago and which provides probably the cleanest and richest example of this new form of nuclear symmetry that has been found so far. An extensive set of experiments and calculations has been performed to study the feeding and decay of states in a superdeformed minimum.

The Argonne gamma group has been involved heavily in the GAMMASPHERE project from its beginning. Tests of complete Compton-suppressed Ge detectors and the design of the BGO suppression shield was carried out at Argonne. One of Argonne's responsibilities within the GAMMASPHERE collaboration is the procurement and testing of the BGO detectors, and coordinating the tests with university groups.

The range of charged-particle experiments has been considerably broadened with the availability of the FMA and the new two-dimensional position-sensitive Si detector array. Exotic cluster states have been studied for $^{24}$Mg which decay into two excited $^{12}$C$(0^+)$ nuclei and subsequently into six alpha particles, showing possible evidence for a 6-alpha-chain configuration.

Some of the nuclear studies at ATLAS are interfaced with atomic physics. Analysis of the charged-state dependence of internal conversion and fluorescence yields has been completed and further experiments with highly-stripped ions are planned with the new PII injector. In the area of astrophysics, the production of secondary $^{17}$F...
beams has been studied. The studies of crystalline beams contained in ion traps or storage rings have continued and first comparisons with experimental data from the ASTRID storage ring in Aarhus have begun.

The Med-ium-Energy Physics program has a major presence in the research program at CEBAF. Members of the group have assumed responsibility for the construction of a broad-purpose, short-orbit spectrometer (SOS). A preliminary engineering design was completed and first funding for component procurement and engineering design was received from CEBAF.

In the study of deep-inelastic scattering of 500-GeV muons in the Fermilab experiment E665, in which Argonne members play a major role, coincidences with leading hadrons have been measured from a variety of nuclei. Noteworthy new results include observation of the ratios of xenon to deuterium cross sections down to x value of $10^{-5}$, two orders of magnitude lower than previously. Also, nuclear shadowing and 2-forward jet events were investigated in detail.

A collaboration between the Argonne group and a Soviet group of physicists at Novosibirsk is engaged in a program of measurements with a tensor-polarized deuterium gas target intercepting the circulating beam. Recently a more advanced target design was developed and tested at Argonne which will allow extension of measurements to large momentum transfers.

At the Stanford Linear Accelerator Center measurements of the photodisintegration of the deuteron were extended during 1990-91 to 4.2 GeV in experiment NE17 in which Argonne provided the leadership. Preliminary results provide strong evidence that the theory of the nucleon-meson description of the reaction is inadequate and the data do appear to scale in a manner consistent with the quark-parton description of the system. In the companion experiment NE18, measurements have been extended to higher values of momentum transfer, never before accessible in (e,e'p) reactions, in the search of color transparency effects.

The study of the weak interaction at low energy is the other major component of the medium-energy physics program. The analysis of an experimental search for neutrino oscillation with a 20-ton neutrino detector positioned near the LAMPF beam stop is just being completed. Neutron beta-decay experiments have been an important component of the program for some time. With the ILL at Grenoble temporarily closed, new experiments to search for time-reversal violation in neutron beta decay will begin at the new cold reactor beam at the NIST reactor in Gaithersburg.

A new experiment to search for the reported 17-keV neutrino was performed during the past year. This experiment employs a superconducting beta spectrometer and a novel technique for reducing the effect of backscattering. An experiment utilizing the technique of laser trapping of neutral atoms began this year. Also, a search for time-reversal violation of beta decay of $^{134}$Cs was started.

In theoretical nuclear physics efforts are continuing to develop theoretical models for describing nuclear dynamics in the kinematic region where hadronic and electromagnetic production of mesons are important. The current focus is in the development of a theoretical approach applicable to the energy regions accessible to CEBAF and other experimental facilities aiming at testing various QCD-based predictions of the excitations of higher-mass nucleon resonances.

The light-front relativistic formulation has been applied to investigate electromagnetic nucleon form factors, high-energy photodisintegration of the deuteron and the spin-structure function of light nuclei. Quark confinement using an approach based on the Schwinger-Dyson equation was studied with the aim to develop a
practical alternative to lattice gauge theory applicable in investigating the interface between QCD and nuclear physics. The consequences of string-like quark models in determining semi-leptonic decay of mesons have been investigated.

Variational Monte Carlo methods have been developed to calculate nuclear properties from realistic two- and three-nucleon potentials. Extensive many-body calculations are being carried out to investigate the correlation effects on nuclear transparency and electron-nucleon scattering.

A three-body model of $^{11}$Li has been developed to successfully describe nuclear reactions induced by heavy ions as well as pions. The focus of our nuclear structure study continues to be the investigation of superdeformation at both high and low spins. Our predictions of various superdeformed nuclei have been confirmed at ATLAS.

In atomic physics research in the Physics Division, the program at ATLAS has continued, aiming at testing relativistic and quantum-electrodynamic (QED) many-body interactions in terms of atomic energy levels and their decay rates. A grazing-incidence monochromator has recently been equipped with a position-sensitive detector. In addition to enhancing the rate of data collection, this detector allows the utilization of the pulsed time structure of the ATLAS facility. Also, studies of atomic collisions using ATLAS beams have been performed including investigations of dielectronic recombination and resonance transfer and excitation. High-precision laser excitation of fast ion beams at the BLASE facility have continued with emphasis on hyperfine structure of metallic and rare-earth ions.

The program of Coulomb-explosion studies of small molecular-ion structures has continued at the Dynamitron accelerator. Major progress has been achieved by developing a new pulsed molecular-ion jet source with cooling that provides molecular-ion beams in their ground state. The Coulomb-explosion program has received special recognition recently by the award of the Rothschild Prize of the Israeli government to Zeev Vager.

A substantial fraction of the atomic physics group has begun a program of synchrotron-based atomic physics research, supported by Argonne as a part of the Lab-wide initiative towards the Advanced Photon Source (APS). The latter, which is now under construction, is expected to be available for experiments at the end of 1995. During the past year the group has collaborated with universities and national laboratory groups in experiments mainly at Brookhaven.

As in the past, the Division had the pleasure of hosting many visiting scientists who participated in our research programs. In addition, the Division has hosted over 50 students ranging from high-school students to graduate students. Education and training of the next generation of scientists is regarded as a significant responsibility of the Physics Division.

Walter F. Henning
Director, Physics Division
August 1992
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The heavy-ion research program of the Argonne Physics Division concentrates on experiments performed at the heavy-ion accelerator ATLAS. ATLAS, with its new positive-ion injector which is presently being commissioned, allows the acceleration of all ions up to uranium with excellent beam qualities and easy energy variability. This versatility of the accelerator and its associated sophisticated experimental equipment is used in a variety of experiments which range from simple Coulomb-excitation studies to the search for exotic particles in collisions between very heavy nuclei. ATLAS is a national user facility with its research time allocated by a Program Advisory Committee.

The effort of the research staff is distributed between on-going experiments and the planning, design, and construction of new experimental equipment. In many of the larger projects major components of the effort come from university groups. The gamma-array, which has a very active research program, has been a joint project between Argonne and the University of Notre Dame. Outside groups have been involved in the design, construction, and testing of experimental equipment at the FMA. The largest new project, the ATLAS positron-electron experiment APEX, is a joint venture of seven institutions. The research program covers a wide variety of experiments involving gamma-ray, positron and charged-particle detection and ranges from simple electromagnetic excitations to studies of nuclei under extreme conditions.

The major part of the research effort was devoted to gamma-ray experiments. The focus of this work has been on the study of superdeformation (SD), especially in the mass-190 region which was discovered at ATLAS three years ago and which provides the cleanest and richest example of this new form of nuclear symmetry that has been found so far and thus has precipitated a flurry of world-wide theoretical and experimental activity. The limits of superdeformation have been probed in some of the experiments and it is now established that $^{189}$Hg is the lightest mercury isotope with a SD band. The band in $^{192}$Hg has been extended to higher spins, showing that, contrary to all theoretical calculations, the dynamic moment of inertia still increases at higher angular momentum. An extensive set of experiments and calculations has been performed to study the feeding and the decay of states in a superdeformed minimum. Based on the mixing between superdeformed and normal states and the electromagnetic decay rates it is now possible to understand the population intensity and the sudden decay of the SD states.

The focus of reflection asymmetric shapes has changed from the mass-150 region to nuclei around $^{225}$Ac, in particular to a study of $^{224}$Ac where large octupole deformations are expected.

The spectrum of charged-particle studies has been considerably broadened with the availability of the Fragment Mass Analyzer (FMA) and a new x-y position-sensitive Si-detector array. The experiments now cover the range from simple one-neutron transfer reactions at large distances to the study of exotic cluster states in sd-shell nuclei and the decay of extremely neutron-deficient heavy nuclei with the FMA. While most of the studies of quasielastic reactions await the beams from the new positive-ion injector, some experiments have addressed open questions in the area of few-nucleon transfer reactions especially in collisions involving deformed nuclei. Using a highly segmented Si-detector array, exotic cluster states have been studied in $^{24}$Mg which decay into two excited $^{12}$C(0$^+$) nuclei and subsequently into 6 alpha particles. The energy and angular dependence of this process is
indicative of a 6-$\alpha$-chain configuration in $^{24}$Mg. First experiments have been performed to study the alpha decays of neutron-deficient Pb and Pt isotopes using the FMA for separation of the residual nuclei, which are produced with very small cross sections.

Many of the studies requiring good time resolutions have been hampered by the present safety requirements which prevent access to the experimental area with beam on target.

The curtailment of the ECR-source operation also postponed a planned development of Accelerator Mass Spectrometry measurements using long-lived isotopes of noble gases ($^{39}$Ar, $^{81}$Kr and $^{85}$Kr), which are of considerable interest because of their chemical inertness.

Some of the experiments at ATLAS are at the interface with atomic physics. The analysis of the charge-state dependence of internal conversion and fluorescence yields has been completed and further experiments with highly stripped Kr ions are planned as soon as the new injector becomes operational. In addition, an experiment about dielectronic recombination of channeled $^{48}$Ti ions has been performed.

In the area of astrophysics the production of secondary $^{17}$F beams has been studied further. Secondary beams which can be produced in inverse (p,n) reactions are of considerable interest in nucleosynthesis studies. The high-current ECR source, together with the modular structure of ATLAS allowing accel-decel techniques, is especially suited for these studies. We are presently investigating the optimum configuration for target, focusing and acceleration structures for these experiments. In addition, specific technical issues for production of secondary radioactive beams out of the ion source are being looked into.

The studies of crystalline beams contained in ion traps or storage rings have continued and first comparisons with experimental data from the ASTRID storage ring in Aarhus have begun.

The installation of the Fragment Mass Analyzer has been completed and first experiments with the full device have started. The ion-optical elements show a mass resolution of one part in 525 and an excellent beam suppression capability has been observed even for inverse reactions. This device will be used in connection with the Compton-suppressed Ge detectors by tagging on particles with a known mass detected in the focal plane of the FMA.

The main components of APEX, the ATLAS positron experiment, have been installed and are presently being tested. This experiment, which studies the peaks found in electron-positron coincidences for collisions between very heavy ions, is a joint effort of six university groups and Argonne. Test measurements using lighter heavy ions are presently being performed and it is expected that the full device will be operational when uranium beams from ATLAS become available.

The Argonne gamma group has, from the beginning, been heavily involved in the GAMMASPHERE project. Tests of two complete Compton-suppressed Ge detectors were performed at Argonne and the design of the BGO suppression shield has been optimized. In addition, detailed studies of the ballistic deficit correction have led to new methods for improving the energy resolution for large Ge detectors. One of Argonne's responsibilities within the GAMMASPHERE collaboration is the procurement and testing of the BGO detectors, which is being done in collaboration with various university groups.
A. CHARGED-PARTICLE STUDIES

This research focuses on three major topics: (a) studies of nucleon transfer reactions in the energy regime close to the barrier and their development from simple one-step processes to complex multi-nucleon processes (b) studies of the production and the decay of exotic cluster states in s-d-shell nuclei and (c) investigations of nuclei far from stability using the Fragment Mass Analyzer.

The experiments use a variety of devices, some of which have been only recently installed at ATLAS. Most of the quasi-elastic reaction studies make use of the Enge split-pole spectrograph and its focal-plane detector system which allows single mass and charge separation for nuclei up to $A = 100$. For the study of cluster states in light nuclei, a highly segmented x-y position-sensitive Si-detector array and the associated readout has been developed which provides a highly efficient system for reactions with many particles in the outgoing channel. The high efficiency of this system allowed a series of experiments which would be very difficult to study using conventional detector systems. The recently installed Fragment Mass Analyzer has been used in first experiments studying nuclei outside the valley of stability. Together with Compton-suppressed Ge detectors it will be a powerful new tool for similar studies in the future.

a. Quasi-Elastic Processes

A large number of quasi-elastic reaction studies have been performed in the last few years using ATLAS with the tandem accelerator as injector. The excellent beam quality of ATLAS was essential for obtaining high-resolution data and good mass resolution for the outgoing particles. An extension of these measurements to heavier projectiles ($A > 100$) which will open up new possibilities for reactions involving nuclei with unique properties (e.g. Sn or deformed rare earth nuclei), was delayed by the curtailment of the operation of the new positive-ion injector.

High-resolution studies of quasi-elastic reactions performed at ATLAS have revealed surprisingly large yields for this reaction mode. The energy, mass, and nuclear charge dependence for these processes has been investigated and a systematic behavior has emerged. Because of their large strength, heavy-ion-induced quasi-elastic reactions can influence other reaction modes, such as fusion and deep-inelastic reactions, especially at bombarding energies in the vicinity of the Coulomb barrier.

In the past year several open questions in the area of quasi-elastic reactions have been investigated. One- and two-neutron transfer induced by $^{58}$Ni projectiles has been studied in spherical and deformed nuclei in order to find out if the simple tunneling description of nucleon transfer breaks down in reactions involving deformed nuclei, as was claimed recently. Our experiments involving $^{208}$Pb and $^{232}$Th targets show good agreement between the experimental results and the tunneling model. The experiments in the systems $^{76,82}$Se + $^{192,198}$Pt addressed an open question about the neutron number dependence of the total quasi-elastic cross section which was first observed in $^{58,64}$Ni-induced reactions on the even Sn isotopes. Furthermore, in a somewhat lighter system $^{160} + ^{90}$Zr the energy dependence of the absolute normalization of one- and two-nucleon transfer cross sections was studied.

The analysis of experiments investigating the charge-state dependence of internal conversion and fluorescent yields in few electron systems ($^{57}$Fe, $^{83}$Kr) has been completed. Relativistic electron wave-function codes are presently being modified to calculate the conversion coefficients for highly stripped ions.
a.1. Neutron Transfer at Large Distances in Spherical and Deformed Systems
(K. E. Rehm, F. L. H. Wolfs, and W. Kutschera)

Quasi-elastic few-nucleon transfer reactions induced by heavy ions are a sensitive probe of the tail of the wave functions of the transferred particles. The transfer probability, as a function of the distance of closest approach, should fall off exponentially with a decay constant that can be calculated from the binding energy of the transferred particle or cluster. While the majority of one-neutron transfer reactions can be well described by this semiclassical description there have been recent measurements indicating that one-neutron transfer on deformed nuclei show deviations from this simple model. We have therefore measured the neutron transfer reactions $^{232}$Th($^{58}$Ni,$^{59,60}$Ni)$^{231,230}$Th at $E_{lab} = 500$ MeV and compared the results to similar reactions on spherical $^{208}$Pb. The experiments were performed at the Enge split-pole spectrograph with a focal-plane detector allowing the separation of individual elements and isotopes. The results for the one-neutron transfer reactions ($^{58}$Ni,$^{59}$Ni) on deformed $^{232}$Th and spherical $^{208}$Pb show no deviations from the decay constants as calculated from the respective binding energies. While good agreement between the experimental and theoretical slopes is obtained for the two-neutron transfer reaction ($^{58}$Ni,$^{60}$Ni) at low bombarding energies, large deviations from the theoretical decay constants are observed at higher bombarding energies.

This is interpreted as due to the stronger localization of the form factors for two-particle transfers which do not allow a description of the reaction in the framework of classical trajectories. These localized transfers are strongly dominated by diffractive effects. This analysis can provide a quantitative understanding of the anomalies observed in the experiments. A paper with the results of these measurements is being prepared.

a.2. Elastic Scattering and Quasi-Elastic Transfer in the System $^{76,82}$Se + $^{192,198}$Pt (F. L. H. Wolfs, K. E. Rehm, J. P. Schiffer, W. C. Ma*, and T.-F. Wang†)

The systematic study of the neutron-number dependence of quasi-elastic transfer cross sections in the Ni + Sn system showed that their strength increases with increasing mass number for the target for $^{58}$Ni-induced reactions, whereas it is constant for $^{64}$Ni-induced reactions. While the neutron-number dependence of the simplest one-neutron transfer cross sections can be understood from the underlying kinematic matching conditions, the dependence of the total quasi-elastic yield on the neutron number of projectile and target is not yet understood. Since for Ni + Sn projectile and target have a closed proton shell we have studied the same effects for the system Se + Pt where shell effects should be minimal. The experiment was performed with the Enge split-pole spectrograph utilizing $^{76,82}$Se beams from ATLAS and $^{192,194,198}$Pt targets. The results show that similar to the Ni + Sn system the total quasi-elastic yields for reactions induced by the neutron deficient isotope $^{76}$Se exhibit an increase with the neutron number of the target while for the neutron-rich projectile $^{82}$Se the quasi-elastic yield remains constant. A paper with the results from these measurements has been submitted for publication.

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a.3. Energy Dependence of One- and Two-Particle Transfer Reactions in the System $^{16}O + ^{90}Zr$ (K. E. Rehm, J. Gehring,* B. Glagola, F. L. H. Wolfs, W. C. Ma†, and W. R. Phillips‡)

The energy dependence of one- and two-particle transfer reactions $^{90}Zr(160,170)^{89}Zr$, $^{90}Zr(160,15N)^{91}Nb$ and $^{90}Zr(160,14C)^{92}Mo$ was studied at bombarding energies of 80 MeV, 138.2 MeV and 194.4 MeV. A comparison with one-step DWBA calculations shows good agreement for the one-particle transfers over the whole energy range. For the two-particle transfer reactions ($^{16}O,^{14}C$) the ratio between experimental and theoretical cross section is about 700 at the lowest energy and shows an exponential decrease towards higher energies. Current theories are unable to describe this behavior. A paper reporting these results has been published.

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a.4. Kinematic Coincidence Measurements of Transfer Reactions in $^{64}Ni + ^{58,60}Ni$, natCu (J. Gehring*, M. Freer, K. E. Rehm, and J. P. Schiffer)

Tests of the mass and energy resolution possible in a kinematic coincidence measurement have been performed for the systems $^{64}Ni + ^{58,60}Ni$ and $^{64}Ni +$ natCu. Targets of 50-$\mu$g/cm$^2$ thickness were bombarded with a $^{64}Ni$ beam of energy 220 MeV. Reaction products were detected in two large-area (20 x 20 cm$^2$) gas counters at a distance of 1.2 m from the target. A mass resolution of 0.6 u and an energy resolution of 2 MeV were observed, allowing the separation of one- and two-nucleon transfer from the elastic scattering reactions. These results are in good agreement with Monte Carlo calculations including the effects of small angle scattering and energy loss in the target along with the intrinsic position and time resolution of the detectors.

The kinematic coincidence technique used in these measurements will now be applied to the measurement of deep-inelastic processes at energies near the Coulomb barrier in the system $^{136}Xe + ^{64}Ni$. Monte Carlo calculations for this system indicate that a mass resolution of better than 1 u should also be possible here. This should allow for a detailed study of the final-state mass distribution and the evolution of this distribution with increasing energy loss.

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a.5. Quasi-Elastic Heavy-Ion Collisions (K. E. Rehm)

A review article was written summarizing the status of quasi-elastic heavy-ion collisions. The paper describes the various techniques available for the study of these processes and discusses their energy, mass, and nucleon charge dependence. Furthermore, the importance of quasi-elastic reactions and their influence on other reaction modes is pointed out. A large part of the data presented in this article was obtained at ATLAS.

Internal conversion (IC) decay rates and fluorescent yields have been measured for $^{57}$Fe ions with different charge states $q$ by observing the distribution of the ions in the focal plane of a magnetic spectrograph. Ions which change their charge because of the internal conversion process during transit through the magnetic field are displaced in the focal plane by an amount which depends on the point in the spectrometer at which IC occurs. The analysis of the data is completed. For comparison with theoretical predictions a program has been developed which calculates conversion coefficients from relativistic electron wave functions for highly stripped atoms. A publication with the results is in preparation.

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a.7. **Charge-State Dependence of the Conversion Decay Rates in $^{83}$Kr** (K. E. Rehm, I. Ahmad, J. Gehring*, B. G. Glagola, W. Kutschera, R. Barnett†, J. Copnel†, and W. R. Phillips†)

The experiments studying the charge-state dependence of internal conversion decay rates have been extended to $^{83}$Kr. The 9.4-keV first excited state in $^{83}$Kr allows the measurement of the $q$-dependence of the L-shell internal conversion coefficient $\alpha_L$. The technique used in the experiment was similar to the one used in our previous study of $^{57}$Fe. The 9.4-keV state was populated by Coulomb excitation of 650-MeV $^{83}$Kr ions on a thin Au target. The charge-state distribution of the $^{83}$Kr ions in the focal plane which is modified by the IC decay processes in the magnetic field allows us to determine the charge-state dependence of $\alpha_L$. The data have been completely analyzed and the conversion coefficients $\alpha_L(q)$ have been measured for $q = 28-33$. Within the experimental uncertainty, $\alpha_L(q)$ stays constant for $q = 28-32$ and shows an increase of about 20% for $q = 33$. It is planned to improve the accuracy for these measurements with an additional run at higher bombarding energies.

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b. **Study of Exotic Cluster States with a Charged-Particle Array**

The study of exotic cluster configurations in light nuclei with $A \leq 56$ and even $N$ and $Z$ has generated a great deal of interest recently. These cluster states have many interesting properties, including very large deformations and unusual decay modes. The nuclear structure of these cluster configurations can have a profound impact on reactions involving such light nuclei. Some examples of experiments of this type include the study of nuclear-structure effects in the breakup of various alpha-particle sd-shell nuclei following inelastic scattering and transfer reactions, as well as other inelastic scattering processes leading to highly-excited, particle unbound states.
In most instances, these reactions lead to final states consisting of several charged particles. A kinematically complete characterization of such reactions therefore typically requires the simultaneous detection of a large number of particles with good energy, time, and spatial resolution. In order to study these processes with high efficiency, and in order to obtain the kinematic information required for the reconstruction of such final states, highly-segmented, high-resolution detectors are required. We have developed and instrumented an array of such devices. The detector elements of the array are large-area silicon PIN diodes, which provide an effective segmentation of 256 pixel regions within a 5 x 5 cm square. By instrumenting these detectors with a combination of custom electronics built at Argonne, and high-density commercial modules, we have developed a powerful system capable of multi-particle detection with the energy, time, and spatial resolution required to study these exotic final states. Several experiments have now been conducted with this array, investigating physical processes that would be either difficult or impossible to study using conventional detector systems.


Before running full-scale ATLAS experiments using the newly instrumented double-sided silicon strip detector (DSSD) array (see I.E.e.), it is important to fully understand the response of the detector elements to multi-particle events. Such tests are impossible to conduct using radioactive sources. In order to test the multiple-particle response of the DSSD's, we have conducted beam tests at the University of Pennsylvania Tandem Accelerator Laboratory. A setup consisting of one DSSD and a large solid-angle gas E-DE telescope was used to study the inelastic scattering of $^{12}$C + $^{12}$C to final states where either one or both of the $^{12}$C nuclei were left in their first-excited 0+ level, which is unbound with respect to decay into three alpha particles. The DSSD, instrumented with prototype multi-channel preamplifiers designed at ANL, was used to measure the energies and angles of the three alpha particles from one decaying $^{12}$C nucleus, while the E-DE telescope detected and identified either intact $^{12}$C nuclei or alpha particles in coincidence.

These measurements showed that the DSSD's could be used to provide X-Y position information for events in which more than one particle strikes the detector. This information was used to reconstruct the kinetic energy, excitation energy and scattering angle for the decaying $^{12}$C nuclei. The resolution of the reconstructed excitation energy for one decaying $^{12}$C was better than 70 keV (see Fig. IA-1). In addition to providing valuable experience for future experiments, the data obtained from these tests also yielded an important

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physics result, the first observation of the $^{12}\text{C} + ^{12}\text{C} + ^{12}\text{C} (0^+; 7.65\text{MeV}) + ^{12}\text{C} (0^+; 9.64\text{MeV})$ inelastic scattering channel (see Fig. IA-1). This result demonstrated the feasibility of the ATLAS experiment approved to study the excitation function for this reaction. The data obtained from these measurements were presented at the International Conference on Nuclear and Atomic Clusters in Turku, Finland.

Fig. IA-1. (Top Panel) Spectrum of $^{12}\text{C}$ excitation energy reconstructed from the energies and angles of 3 alpha particles detected in one DSSD, at $E_{\text{lab}} = 58\text{ MeV}$. The resolution for the $0^+(7.65\text{ MeV})$ state is 70 keV FWHM. (Bottom Panel) Reconstructed two-body scattering $Q$ value for coincidences between one $^{12}\text{C}(0^+; 7.65\text{MeV})$ fragment, and either a $^{12}\text{C}$ nucleus or an alpha particle in the E-AE telescope. The $0^+ - 0^+$ final state is at $Q = -15.30\text{ MeV}$. 

In the early study of nuclear synthesis of the element $^{12}$C in stars, one of the major concerns was accounting for its observed abundance. The creation of $^{12}$C appeared to be blocked by the instability of the elements at masses $A = 5$ and 8, e.g. $^8$Be which decays into two alpha particles with a lifetime of $1 \times 10^{-16}$ seconds. Clearly it is important to understand the process by which $^{12}$C is created, as it directly effects the abundances of many heavier elements.

The creation of $^{12}$C is currently thought to occur via a two-stage process, the first stage being the fusion of two $^4$He nuclei to form $^8$Be in its ground state. The second stage requires that the resulting $^8$Be fuses with a further $^4$He nucleus before it decays. The resulting $^{12}$C nucleus is proposed to be formed in a resonance state (7.68 MeV, $^0_+\$), close to the $^4$He + $^8$Be threshold, which then deexcites to the $^{12}$C ground state either by two-photon emission or via electron-positron pair conversion. These methods of deexcitation of the $^{12}$C state have been found to compete weakly with alpha decay, but result in approximately 1 in 2500 of the $^{12}$C nuclei produced decaying to the $^{12}$C ground state. Such a deduction is based upon the assumption that the magnitude of the three-alpha-decay contribution to the total width of the state is small and can be neglected. However, the partial decay width for the decay into three alphas is unknown, but if significant, could result in modifications of the deduced abundance of $^{12}$C and more importantly most other heavier elements.

Rather than study the fusion process, we have performed a measurement from which we are able to deduce the relative decay probabilities for the $^8$Be + $^4$He and three alpha channels. This measurement involved the inelastic excitation of the $^{12}$C nucleus following scattering from a $^{12}$C target at a beam energy of 56 MeV. The resulting decay of the $^{12}$C(0\(^+\)) state into either $^8$Be + $^4$He or three alphas, both of which give rise to three alpha particles in the final state, was detected using a double-sided strip detector (see I.E.e.). The high degree of segmentation resulted in a relatively high efficiency for detecting all three alpha particles. The recorded energy and angle information for each particle enabled the reconstruction of both the Q value for $^{12}$C + 3 alpha and the two-body reaction Q value. By this means we were able to focus the analysis on $^{12}$C($^{12}$C, $^{12}$C(0\(^+\)))$^{12}$C events. The number of events in which the $^{12}$C(0\(^+\)) decayed into $^8$Be + $^4$He was deduced through a determination of the two-body Q values for all pairs of the three alpha particles. This enabled us to isolate the two-body decay channel, which constituted 86% of the events. A Monte Carlo simulation of the detection process indicates that a large fraction of the remaining events can be associated with misassignment of the detection angles caused by ambiguities in the strip assignment (see Fig. IA-2). This would appear to be confirmed by a detailed analysis of these events. It may be concluded from this measurement of the three-alpha branching ratio from the decay of $^{12}$C(0\(^+\)) that the partial decay width is less than a few percent of that of the two-body decay mode.

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Fig. IA-2. A comparison between calculated relative energies of the three a-particles for the experimental data (top) and the Monte Carlo simulation (bottom). The simulation is for the decay of the 12C(0) state into the 8Be + 4a chain, with the effects of the angular ambiguities included which give rise to most of the observed background. Erel₁, Erel₂, and Erel₃ refer to the relative energy between the a-particles, each particle being ordered by its energy, i.e., 1 is more energetic than 2, etc.
b.3. Energy Dependence of the $^{12}\text{C} + ^{12}\text{C} + ^{12}\text{C}(0^\frac{+}{2}) + ^{12}\text{C}(0^\frac{+}{2})$ Inelastic Scattering Reaction (A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, B. G. Glagola, Th. Happ, D. J. Henderson, P. Wilt, and I. G. Bearden*)

One intriguing prediction of many models employed to describe the nuclear structure of alpha-particle sd-shell nuclei, including the cranking model and alpha-cluster models, is the existence of an extremely deformed configuration, which in an alpha-cluster picture corresponds to linear chains of alpha particles. In the nucleus $^{24}\text{Mg}$, such a configuration corresponds to a very highly prolate-deformed shape with a 6:1 axis ratio. Calculations predict, however, that such a configuration would lie well above the threshold for decay of $^{24}\text{Mg}$ into its 6 constituent alpha particles. The identification of such a structure thus provides a distinct experimental challenge.

One likely decay mode for such a level in $^{24}\text{Mg}$ is to $^{12}\text{C}(0^\frac{+}{2}) + ^{12}\text{C}(0^\frac{+}{2})$. The first excited $0^+$ state in $^{12}\text{C}$ is described primarily as a linear 3-alpha particle structure. Structural and phase-space considerations thus strongly favor the decay of a 6-alpha chain by symmetric breakup into two 3-alpha particle chains, corresponding to a final state consisting of two $^{12}\text{C}$ nuclei in their first excited $0^+$ state. In a $^{12}\text{C} + ^{12}\text{C}$ inelastic scattering experiment, resonance-like features observed in the excitation function for mutual $0^+_2$ channels could be a likely signature for the formation of this 6-alpha chain structure.

At 7.65 MeV, the $^{12}\text{C}(0^\frac{+}{2})$ lies 380 keV above the threshold for decay into 3 alpha particles. We have used a setup consisting of two large-area segmented double-sided silicon strip detectors (DSSDs) (see I.E.e.) to detect the three alpha particles emerging from the decay of one or both of the excited $^{12}\text{C}$ fragments, at laboratory energies between $E(\text{lab}) = 52$ to 80 MeV. Due to the small amount of breakup energy available, the 3 alpha particles are confined within a narrow cone around the direction of the primary scattered $^{12}\text{C}$ nucleus. The kinematic information provided by the strip detectors allows us to reconstruct the kinetic energy, excitation energy, and scattering angle of the decaying $^{12}\text{C}$. The observed resolution for the reconstructed $^{12}\text{C}$ excitation energy from three alpha particles detected in one strip detector was better than 70 keV. From the reconstructed kinetic energy and scattering angle of a single $^{12}\text{C}$ fragment, we can also obtain the two-body $Q$ value, and hence identify the mutual $^{12}\text{C}(0^\frac{+}{2})$ channel (see Fig. IA-3). We have observed a strong peak in the mutual $^{12}\text{C}(0^\frac{+}{2})$ excitation function at center-of-mass energy of $E_{\text{cm}} = 32.5$ MeV (see Fig. IA-4). The properties of this excitation-function structure are consistent with those expected for the population and subsequent decay of a linear 6-alpha particle configuration in $^{24}\text{Mg}$. A manuscript describing these results has been published1.

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Fig. IA-3. Reconstructed two-body scattering $Q$ values for $^{12}\text{C} + ^{12}\text{C}$ inelastic scattering, for coincidences between one identified $^{12}\text{C}(0^+2)$ in one DSSD, and either an alpha particle or a $^{12}\text{C}$ nucleus in the other DSSD. The $0^+2 - 0^+2$ mutual excitation is at $Q = -15.30$ MeV.

Fig. IA-4. Excitation function for $^{12}\text{C} + ^{12}\text{C} + ^{12}\text{C}(0^+2) + ^{12}\text{C}(0^+2)$ mutual inelastic scattering. Shown is the differential cross section averaged over the angular range of the detector setup, $70^\circ < \theta_{\text{c.m.}} < 105^\circ$. The Lorentzian fit to the data (solid curve) gives $E_c = 32.5$ MeV and a width of $\gamma_{\text{c.m.}} = 4.7$ MeV.
b.4. **Angular Distribution Measurements for $^{12}C + ^{12}C \rightarrow ^{12}C(0^+) + ^{12}C(0^+)$**


The observation of a strong resonance-like peak in the excitation function for the inelastic scattering of $^{12}C + ^{12}C$ to the mutual $^{12}C(0^+)$ final state suggests that in this reaction we may be populating exotic, highly prolate deformed alpha-particle chain configurations in the composite system $^{24}Mg$ (see I.A.b.3.). Such chain configurations are predicted to occur by several theoretical models describing the structure of $^{24}Mg$. In order to obtain some more detailed information about this system, with which to compare the theoretical expectations for linear alpha-particle structures in $^{24}Mg$, we have obtained detailed inelastic scattering angular-distribution data for the mutual $^{12}C(0^+)$ channel. Since the particles in the two-body final state each have spin 0, the $^{12}C + ^{12}C$ inelastic scattering angular distribution contains information which can be related directly to the angular momenta involved in this scattering process.

Angular distributions were measured at 8 energies in the vicinity of the excitation-function peak for this channel. Two double-sided silicon strip detectors (DSSDs) (see I.E.e.) were used to detect the three alpha particles from the decay of one of the two $^{12}C$ nuclei, at angles ranging from 7 to 45 degrees in the laboratory. The x-y position measurement for the three alpha particles obtained from the DSSD allows the reconstruction of the kinetic energy, scattering angle, and excitation energy of the decaying $^{12}C$, as well as the Q value for the initial two-body scattering process. The analysis of the data obtained in this experiment is continuing, and a thorough analysis of the resulting angular distributions should tell us much about the angular momenta contributing to the very prominent peak in the inelastic scattering excitation function. Preliminary results suggest that angular momenta in the range of $L = 14-16$ play a significant role in this reaction at these center-of-mass energies (see Fig. IA-5).

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Fig. IA-5. Angular distribution data for $^{12}\text{C},^{12}\text{C} + ^{12}\text{C}(0+2) + ^{12}\text{C}(0+2)$ inelastic scattering at center-of-mass energies of 28.5, 31.0, 32.5, and 34.5 MeV. The solid curves are $p_{14}(\cos\theta)^2$ for $E_{\text{c.m.}} = 28.5$ and 31.0 MeV and $p_{16}(\cos\theta)^2$ for $E_{\text{c.m.}} = 32.5$ and 34.5 MeV.
b.5. **Sequential Fission of States in $^{24}$Mg** (M. Freer, A. H. Wuosmaa, B. B. Back, R. R. Betts, J. Gehring*, Th. Happ, D. Henderson, and P. Wilt)

A series of studies of the symmetric fission of $^{24}$Mg following inelastic scattering from $^{12}$C targets has demonstrated that the breakup of the excited $^{24}$Mg nucleus arises from specific states in the excitation region 20 to 30 MeV. The spin-energy systematics of these states are characteristic of a rotational structure with a large moment of inertia, consistent with a $^{24}$Mg nucleus with a 3:1 deformation. Such states may be associated with shape isomeric configurations stabilized by minima in the potential energy of $^{24}$Mg at large deformations. Although the origin of the breakup states may be becoming clearer, the nature of the nuclear interaction between the $^{12}$C target and the $^{24}$Mg beam by which they are populated is far from understood. The shape isomeric configurations have been associated with quite exotic particle-hole configurations which are unlikely to be populated through direct inelastic excitation. Thus the reaction mechanism may be related to a more complex excitation mechanism, e.g. orbiting. In this particular study of the reaction $^{12}$C($^{24}$Mg, $^{24}$Mg* + $^{12}$C + $^{12}$C)$^{12}$C we concentrated on measuring the primary angular distribution of the $^{24}$Mg*. Such a measurement is complicated by the need to detect a large fraction of the $^{12}$C breakup fragments which the decay of the $^{24}$Mg* produces. In order to measure the primary angular distributions over the entire range of scattering angles a large angular and energy acceptance is important. Four double-sided silicon strip detectors (DSSDs) were used to detect coincidences between any two of the three final-state $^{12}$C nuclei. These large-area detectors enabled us to cover the angular region 6 to 40 degrees on one side of the beam and the intervals 6 to 22 degrees and 38 to 52 degrees on the other. Such an arrangement allowed us to measure the primary angular distribution in a single setting with a relatively high coincidence detection efficiency ($\sim 7 - 10\%$). This experiment was a major undertaking, requiring the processing of more than 256 channels of information, and marks a significant step forward in terms of the instrumentation of the DSSDs.

In addition to the symmetric breakup channel, these strip detectors allowed us to measure simultaneously the breakup of $^{24}$Mg into the asymmetric channel $^{16}$O + $^{8}$Be, the detection of which is complicated by the need to detect two alpha particles from the decay of the $^{8}$Be in flight. The high segmentation of the detection system provided a means for detecting efficiently the two alpha particles, in adjacent strips, in coincidence with a $^{16}$O nucleus. Furthermore, this experimental arrangement presented us with the opportunity to observe the breakup of the $^{24}$Mg* nucleus into $^{12}$C + $^{12}$C(0$^+$), a decay mode which was predicted to occur from some of the shape isomeric configurations. Such a reaction has been unobserved previously due to the complication of the decay of the $^{12}$C(0$^+$) state into 3 alpha particles. As demonstrated in (I.E.e.) the DSSDs are excellent tools for the measurement of such a reaction process. The analysis of these data is continuing, and is expected to reveal important information regarding the nature of the $^{12}$C + $^{24}$Mg interaction which leads to the population of shape isomeric configurations and also their preferred decay modes.

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c. **Fusion and Fission with Heavy-Ion Beams**

The study of fusion and fission(-like) reactions with heavy-ion beams constitutes an ongoing effort at ATLAS. The aim of this program is to investigate the dynamics of fusion and fission-like processes, as well as utilizing the heavy-ion fusion process to produce and study isotopes far from stability by means of the new Fragment Mass Analyzer instrument.

Studies of the angular distributions of the fission fragments have shown that the angular momentum distribution in subbarrier fusion processes extend to higher spin values than predicted by current theories, despite the fact that these theories are very successful in explaining the overall fusion cross sections at these energies. One experiment using the reactions $^{16}O + ^{208}Pb, ^{232}Th$ has been performed to study this effect.

Heavy-ion fusion reactions between neutron-deficient targets and projectiles constitute an effective method for producing very neutron-deficient isotopes. The new Fragment Mass Analyzer at ATLAS, which has proved to have a mass/charge resolution equal to or exceeding the design goal of 1/350 is an instrument very well suited for separating and identifying such products. A first measurement in this program has been carried out using the reaction $^{32}S, ^{40}Ca + ^{144,147}Sm$ to study neutron-deficient Pb and Pt isotopes.


The sub-barrier angular distributions of the $^{16}O + ^{208}Pb, ^{232}Th$ reactions were studied at beam energies of 76.1, 77.4, 78.4, 80.0, and 81.5 MeV, respectively. A new experimental setup, which employs 23 400-mm$^2$ Si detectors located at a distance of about 20 cm from the target was used. This setup allowed the measurement of the entire angular distribution from 50$^\circ$ to 170$^\circ$ in 10$^\circ$ steps, in a single run with special emphasis on the angles near 90$^\circ$ and 180$^\circ$ in the CM system. These angles are most important for a determination of the angular anisotropy.

Using the time-of-flight measurement based on the radio-frequency of the machine, it was possible to separate the two fission components from compound fission and sequential fission of target-like recoil products, in the case of the $^{232}Th$ target. For the $^{208}Pb$ target there is no appreciable sequential fission component owing to the low fissility of the $^{208}Pb$ target. The measured anisotropies of the angular distributions are in good agreement with earlier measurements of inferior quality. They do, however, corroborate the conclusion reached earlier, that the sub-barrier fission anisotropies are substantially larger than expected from the most recent fusion calculations. No satisfactory explanation for this discrepancy has yet been proposed.

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The alpha decays of neutron-deficient Pb and Pt isotopes were studied in a preliminary FMA experiment in which targets of $^{144}$Sm and $^{147}$Sm were bombarded by $^{32}$S and $^{40}$Ca beams. The fusion products that reached the FMA focal plane passed through the parallel-grid avalanche counter (PGAC) and implanted themselves in a 25-mm diameter Si detector placed 25 cm behind the focal plane. Since the scattered beam particles and the heavy recoils had comparable energy losses in the PGAC, the energy-loss method of discrimination between the two particle species could not be used. Instead, the time-of-flight between the PGAC and the Si detector was measured, allowing the two types of particles to be separated cleanly.

Using the ATLAS fast beam sweeper, prompt and delayed alpha spectra were accumulated. The delayed spectra are extremely clean, and show only the implanted alpha activities as well as daughters and granddaughters. Activities with half-lives down to 40 ms were observed easily. When a high-intensity $^{40}$Ca beam becomes available from the ATLAS positive-ion injector, a search for Pb isotopes near $^{180}$Pb will be conducted.

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B. GAMMA-RAY SPECTROSCOPY STUDIES

This research program focuses on two major areas: (a) studies of nuclear properties associated with very elongated nuclear shapes (superdeformed states), and (b) investigations of the evolution of the nuclear shape as a function of proton and/or neutron number as well as a function of angular momentum and temperature (excitation energy above the yrast line).

A major focus of the Argonne work has been on the study of superdeformation. Work at this laboratory has provided first evidence for a new region of the periodic table where superdeformation occurs: the A ~ 190 region. First evidence was found in $^{191}\text{Hg}$ and considerable effort has been focussed over the last three years on studying the properties of superdeformed nuclei in this region in great detail.

All projects described in this section have taken advantage of the capabilities of the Argonne-Notre Dame BGO γ-ray facility which consists of 50 hexagonal BGO detectors (used mainly as a sum-energy/multiplicity filter) surrounded by 12 Compton-suppressed Ge detectors. A wide variety of computer programs are available from the collaboration which provide assistance with setting up the experiments (gain matching, adjustment of constant-fraction discriminators, offset settings on ADCs, etc.) and with data reduction and analysis (sorting of the events into γ-γ coincidence matrices under a variety of gating conditions, peak fitting routines, etc.). A scattering chamber for coincidence measurements between γ rays and particles identified by either AE-E or time-of-flight techniques is also available. A plunger apparatus for recoil-distance measurements of nuclear lifetimes has been developed by the Notre Dame group. The device fits entirely inside the BGO array. Dedicated chambers have been constructed for other experiments as well (g-factor measurements, fission-fragment coincidence measurements, etc.). A support for up to 7 Compton-suppressed spectrometers at the magnetic spectrograph is also available and the construction of a support for ten Compton-suppressed spectrometers at the target position of the Fragment Mass Analyzer (FMA) has been completed. A dedicated scattering chamber for use of the γ-ray detectors at the FMA is being developed.

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

a. Superdeformed Nuclei

Following calculations by R. Chasman, we reported three years ago on evidence for the existence of a new region of superdeformation around $^{192}\text{Hg}$. ATLAS work has found superdeformed bands in a chain of Hg nuclei with $A = 189-192$, and in $^{193}\text{Tl}$. More recently, superdeformed bands have also been investigated in $^{192,195,196}\text{Pb}$ and $^{191}\text{Tl}$. There are several interesting aspects to superdeformation in the A ~ 190 region. First, all factors contributing to the formation of a superdeformed pocket in the nuclear potential come into play: rotation and Coulomb energy as well as shell effects. Second, the superdeformed bands persist to low spins, giving rise to low transition energies which can be efficiently detected, and open opportunities for detailed measurements of their properties. Furthermore, because lower spins and
rotational frequencies are involved in this region when compared to the A ~ 150
region (where superdeformation has also been observed), the comparison of the
properties observed in the bands of both regions should be particularly
revealing.

For all superdeformed nuclei in the mass-190 region, the dynamic moments of
inertia are observed to increase with rotational frequency. Lifetime
measurements of individual members of the superdeformed band in $^{192}\text{Hg}$
discussed in earlier reports have allowed us to show that this increase is
not due to centrifugal stretching. Cranked shell-model calculations including
monopole pairing have been performed. They have proven to be very successful
in reproducing the data. It is a direct consequence of these calculations
that, after the quasiparticle alignments have taken place, the dynamic moment
of inertia $J^{(2)}$ will exhibit a downturn with increasing rotational frequency
and will approach the value of the static moment of inertia $J^{(1)}$. In a very
recent study, we were able to extend the band of $^{192}\text{Hg}$ to higher rotational
frequencies than had been possible earlier. We have been able to show that
$J^{(2)}$ keeps rising with rotational frequency, even at the highest frequencies.
This result raises questions regarding the applicability of the cranked shell
model under its present form. In particular, it may imply that higher-order
corrections to monopole pairing have to be taken into account. The importance
of other effects such as the role of octupole instabilities or residual
neutron-proton interactions also requires attention.

Experiments at ATLAS have continued to explore the properties of superdeformed
nuclei in this region. The superdeformed band of $^{189}\text{Hg}$ has been extended to
higher frequencies and the transition energies have been determined with better
accuracy. This turns out to be important as this superdeformed band represents
one of the few instances where fitting techniques developed to estimate the
spins of the superdeformed states clearly fail. Studies of proton excitations
in the second well of $^{191}\text{Tl}$ have been performed in order to investigate the
role of the $1\frac{3}{2}$ proton orbital. Investigations of the properties of
superdeformed bands in the Pb isotopes have been initiated with the aim of
looking for possible effects of octupole deformation. Questions concerning the
properties associated with the feeding and the decay of the superdeformed bands
near A = 190 have also been addressed.

One of the most remarkable and unexpected properties discovered in
superdeformed bands is the extremely close coincidence in the energies of $\gamma$
rays between certain pairs of bands in different nuclei. This property is now
well documented for superdeformed nuclei in both the A = 150 and A = 190
regions. Recently, we were able to show that the observation of such bands is
surprising, but perhaps not as unique as thought previously. We have found
"identical" transition energies in the ground-state bands of $^{240}\text{Pu}$, $^{224,246}\text{Cm}$
and $^{250}\text{Cf}$ (up to spin 8$^+$) and the corresponding transitions in the ground-state
bands of $^{236}\text{U}$ and $^{238}\text{U}$ are also within ~ 2 keV of each other up to 24 $^+$.
The experimental observations cannot be readily accounted for in the cranked shell-
model calculations and may require the introduction of new concepts. In
particular, the concept of pseudo-spin symmetry has been introduced to account
for some of the "identical" bands in the A = 150 region. For example, the two
bands in the nuclei $^{152}\text{Dy}$ and $^{151}\text{Tb}$ can be understood within the strong-
coupling limit of the particle-rotor model if the decoupling parameter $a$ is
precisely $a = 1$. Within the pseudo-spin scheme, the value $a = 1$
emerges for the pseudo-orbitals involved. If this explanation holds, an excited superdeformed band with a decoupling parameter \( a = -1 \) is predicted to occur in \( ^{151}\text{Dy} \). The first superdeformed band in this nucleus was discovered at Argonne several years ago, and it seemed natural to check the proposed model for this nucleus. A high-statistics experiment has been performed at Chalk River. Thus far, the results of this search have been negative.

Superdeformation occurs because of the occurrence of a secondary potential minimum which, at low spin, lies higher than the minimum corresponding to the normal states. In other words, it represents a false vacuum. Through an extensive set of measurements and calculations we are now able to understand and describe how the compound nucleus "falls" into and out of this false vacuum. Measurements to elucidate the feeding mechanism have been made of (a) spin and sum-energy distributions associated with feeding of normal and SD states at several bombarding energies, (b) entry distributions in the two-dimensional spin/sum-energy space at one beam energy, and (c) of SD band transition intensities as a function of spin. To understand why the SD band suddenly decays to normal states we are in the process of isolating the spectrum of the decay \( \gamma \) rays.

We have developed a model to follow the history of SD bands from formation to decay. The model can successfully account for the SD entry distributions, the population intensities of SD bands and the variation of intensities with spin. Calculations of the decay can account for the sudden decay out of the SD band. In both the feeding and decay of SD bands, the physics involves mixing between SD and normal states and the electromagnetic rates in both SD and normal wells. In turn, the mixing is governed by the coupling (tunnelling) between the SD and normal states and their relative level densities.

We can now understand the mechanisms for feeding and decay of SD bands. Furthermore, comparison of data and calculations leads to constraints on the energy of SD bands and on the SD well depth.
The evolution of dynamic moments of inertia $J(2)$ as a function of the rotational frequency $\hbar \omega$ for the SD bands in the mass-$A = 150$ region is characterized by pronounced isotopic and isotonic variations which have been attributed to differences in the occupation of specific high-$N$ intruder orbitals. In contrast, all but two of the SD bands in the mass-$A = 190$ region display the same overall behavior: a smooth and rather pronounced increase of $J(2)$ with $\hbar \omega$ is always present.\(^1\) It has been shown that the occupation of specific high-$N$ intruders cannot account for this observed rise in $J(2)$.\(^2\) The nucleus $^{192}$Hg is often regarded as the doubly-magic SD nucleus in the $A = 190$ region as large shell gaps are calculated to occur in the single-particle spectrum for $Z = 80$ and $N = 112$, at a quadrupole deformation $\beta_2 \sim 0.55$.

Experiments performed at ATLAS which were described in earlier reports yielded the following results: (1) a single SD band has been found in this nucleus, (2) the measurement of the lifetimes of the individual SD states conclusively shows that a change in deformation with $\hbar \omega$ (centrifugal stretching) cannot explain the observed $\sim 40\%$ rise in $J(2)$, and (3) calculations using the cranked Woods-Saxon Strutinsky model with pairing are able to account for the general trend seen in the data. The rise in the calculated $J(2)$ can be ascribed to the combined alignment of a pair of $N = 6$ ($i_{13/2}$) protons and a pair of $N = 7$ ($j_{15/2}$) neutrons. It is a direct consequence of this type of calculation that, after the quasiparticle alignments have taken place, $J(2)$ will exhibit a downturn with increasing $\hbar \omega$ and will approach the value of the static moment of inertia $J(1)$.

In the present work, the SD band of $^{192}$Hg has been extended to a frequency $\hbar \omega \sim 0.44$ MeV, i.e. the highest frequency reached in this mass region, hereby providing a test of the calculations mentioned above. This was achieved by combining the results of five experiments originally performed to study the population of the $^{192}$Hg SD band in the $^{160}$Gd($^{36}$S,4n) reaction at beam energies varying from 154 to 167 MeV. The total data set comprised $2.8 \times 10^8$ coincidence events, of which $\sim 7\%$ are of higher order (mainly triple $\gamma-\gamma-\gamma$ events). In the analysis, a coincidence matrix was constructed where events corresponding to high-multiplicity cascades in $^{192}$Hg were enhanced by careful selection of conditions on the $\gamma$-ray multiplicity and on total energy recorded in the array. The final matrix obtained in this way contained $2.0 \times 10^7$ events. The triple coincidence events were also sorted separately in a so-called coincidence cube where the energies recorded in the three detectors are stored along each one of the principal axes. The total number of triple coincidence events analyzed was $4.2 \times 10^6$.


The spectrum obtained by adding the cleanest coincidence spectra (Fig. IB-1) revealed three new candidates with respective energies of 820.7, 847.6 and 874.0 keV. These γ-rays also appear in individual coincidence spectra even though they are very weak. Thus, there is a need for further confirmation from the analysis of the γ-γ-γ triple events. The triple coincidence spectra confirm the presence of the transitions at 821 and 848 keV and make the assignment of the highest transition at 874 keV plausible.

![Image of γ-ray spectrum in 192Hg](image)

**Figure IB-1.** γ-ray spectrum in 192Hg obtained by summing the cleanest coincidence gates placed on the 257-, 300-, 341-, 381-, 496-, and 602-keV transitions in the γ-γ coincidence matrix described in the text. Known 192Hg yrast transitions are identified with a * symbol. The inset shows the relative intensity of the SD lines as measured in the 341-keV coincidence spectrum.
In contrast with the expectations based on cranked-Strutinsky models, $J^{(2)}$ keeps rising over the entire $\hbar \omega$ range (Fig. IB-2). This observation points to the need to question the alignments indicated by the model and to reexamine the underlying physics. Within the cranked-shell model, variations of several parameters which influence the evolution of $J^{(2)}$ with $\hbar \omega$ have been explored. Small changes in the deformation parameters $\beta_2$ and $\beta_4$ allowed by our lifetime measurements result in minor changes in the frequency at which the high-$N$ proton and neutron intruders align. These changes will, however, not delay the downturn of $J^{(2)}$ beyond the frequency range under consideration. We have studied the effects of introducing a static octupole deformation $\beta_3$. The interaction strength between crossing levels increases with $\beta_3$ for neutrons and decreases for protons. Again, the effects on $J^{(2)}$ remain small. In most cranked-shell model calculations which attempt to reproduce the evolution of $J^{(2)}$ with $\hbar \omega$ in the $A = 190$ region, the most critical parameter appears to be the monopole pairing strength, but pairing has thus far been treated mainly as a parameter for which a detailed microscopic treatment is not yet available. Reduced pairing is to be expected on the basis of general arguments. If the monopole pairing strength is indeed reduced, higher-order corrections such as quadrupole pairing may become important. Efforts to explore this possibility are currently under way for the SD nuclei in collaboration with Chasman, Wyss and Nazarewicz. A paper reporting these results has been accepted for publication in Phys. Lett. B.

Fig. IB-2. Comparison between the measured and calculated (solid line from Ref. 2, dashed line from Ref. 3) dynamic moments of inertia $J^{(2)}$ as a function of rotational frequency $\hbar \omega$ in the SD band of $^{192}$Hg. As customary for this type of figure, the frequencies are calculated from the average of two consecutive transition energies.

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a.2. Characterization of the Superdeformed Band in $^{189}\text{Hg}$


The existence of an "island" of superdeformed (SD) nuclei in the vicinity of $A = 190$ is well established. In an experiment designed for the study of superdeformation in $^{190}\text{Hg}$ (see Ref. 1), we had found a weak SD band which was assigned to $^{189}\text{Hg}$ on the basis of the available coincidence information. However, this information was rather fragmentary since, at the selected beam energy, the intensities of the measured transitions were very weak. In a subsequent experiment designed to optimize the yield in the $^{189}\text{Hg}$ SD band, additional transitions have now been observed and the decay towards the yrast line has been elucidated.

The experiment was performed at ATLAS with the Argonne-Notre Dame BGO $\gamma$-ray facility. The $^{160}\text{Gd}(^{34}\text{S},5n)$ reaction at 165 MeV was selected to populate the highest spin states in $^{189}\text{Hg}$. All the SD lines found in the earlier experiment have been observed here as well. The improved statistics results in a more precise determination of the transition energies in the SD band as well as in its extension by at least one, and more likely two, additional transitions (Fig. IB-3). Furthermore, the SD $\gamma$ rays are clearly in coincidence with known yrast transitions in $^{189}\text{Hg}$. Thus, there is no remaining uncertainty concerning the assignment of this band to $^{189}\text{Hg}$.

Fig. IB-3. The SD band of $^{189}\text{Hg}$. 
Several related procedures for assigning spins to SD states in the $A = 190$ region have been proposed recently. They rely mainly on the fitting of the experimental $J^{(2)}$ values with the expression $J^{(2)} = J_0 + 3J_1 \omega^2$, where $\hbar \omega = E / 2$. The constants $J_0$ and $J_1$ are obtained from the fit and are then related to the spin $I$ by the equation $I + 1/2 = J_0 \omega + J_1 \omega^3 + i_0$. The so-called intrinsic alignment $i_0$ is a constant of integration which is often assumed to be zero. This assumption has been the subject of considerable debate. We note that in the case of the $^{189}$Hg SD band, the least-squares fit results in a value of 15 $\hbar$ for the lowest SD state, i.e. an integral value, which is not possible for an odd-even nucleus. This difficulty leads one to consider at least two possibilities. First, it is conceivable that the problem simply reflects the inadequacy of the fitting procedure. Another possibility is that the hypothesis of a zero intrinsic alignment is not correct. A non-zero value for $i_0$ is, in fact, not unexpected as the SD band configuration most likely contains the $73/2$ high-$j$ intruder neutron orbital and it has been pointed out that poor fits with the expression given above are most common when SD bands built on intruder configurations are involved. However, even if this second possibility is considered, the surprising fact remains that the intrinsic alignment has precisely a half-integral value, a feature for which there is currently no explanation from theory.

The feeding pattern of the yrast states by the SD cascade has been delineated, and an average yrast entry spin $I_{in}$ of 14.5 $\hbar$ is derived from the data. It is interesting to compare this value with those obtained for the SD bands in $^{190}$Hg ($I_{in} = 10.5$ $\hbar$) and in $^{192}$Hg ($I_{in} = 8$ $\hbar$). We note that the value of $I_{in}$ decreases with increasing mass number, suggesting that the decay out of the SD band occurs from a SD level with lower spin for heavier mass. This feature, in turn, correlates nicely with the observation that the lowest transition energy in the SD band also decreases with increasing mass from 366 keV ($^{189}$Hg) to 360 keV ($^{190}$Hg) and 257 keV ($^{192}$Hg). Thus, rotational energy and spin appear to be correlated to some degree.

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We have recently embarked on a study of superdeformation in the Pb isotopes with the following general motivations: (1) the Pb nuclei are calculated to show rather strong octupole effects for which experimental evidence is currently at best rather weak, (2) finding excited bands in these isotopes would help to elucidate questions regarding the neutron and proton single-particle energies in the vicinity of the Fermi surface at large deformations, (3) the possible discovery of so-called "identical" bands, i.e. bands with transition energies essentially identical to those observed for superdeformed bands in neighboring nuclei, would allow us to test some of the explanations proposed to account for this unexpected phenomenon.

We have used the $^{170}$Er($^{30}$Si, 4 and 5n) reactions to study the nuclei $^{196,195}$Pb with ATLAS beams of 146-155 MeV. Use was made of the Argonne-Notre Dame BGO $\gamma$-ray facility. The analysis has only recently begun. At this point, the following conclusions can already be drawn: (1) a band reported earlier by Brinkman et al.\(^1\) is observed in our data. One transition has been added at the bottom of the band, three other $\gamma$ rays have been added to the high-energy end of the spectrum, and the energies of the highest observed transitions in the band appear to require some correction. (2) Our preliminary analysis leads us also to question, to some degree, the isotopic assignment to $^{196}$Pb of this band, as some yrast transitions in $^{195}$Pb appear to be in coincidence with the lines mentioned above. (3) Preliminary evidence has also been found for additional band structures with energy spacings suggestive of superdeformation ($\Delta E_\gamma \sim 35$-40 keV). Here again, isotopic assignments are at present uncertain.

The analysis is continuing. Additional experiments are planned at higher beam energies in order to address in greater detail questions regarding isotopic assignments.

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The Livermore-Berkeley collaboration has recently reported a superdeformed band of nine transitions in the $^{192}$Pb nucleus. This result appeared somewhat surprising since cranked Strutinsky calculations by Chasman and Nazarewicz et al. indicated little or no superdeformed minimum in the total energy surface of this nucleus. In order to investigate this case further, we decided to attempt a measurement of the deformation associated with this band by determining the lifetimes associated with the observed transitions.

As in the experiment mentioned above, use was made of the $^{173}$Yb($^{24}$Mg, 5n) reaction at a beam energy of 132 MeV in order to populate the states of interest. The target consisted of a 980-μg/cm$^2$ isotopically enriched $^{173}$Yb layer evaporated on a 15.2-mg/cm$^2$ Au backing. Thus, the recoiling nuclei decay while slowing down in the Au layer and lifetimes can be obtained from Doppler broadened shapes (DSAM technique) if lifetimes are shorter than the slowing-down time in the stopper foil. The measurements were performed at the Argonne-Notre Dame BGO γ-ray facility.

All the lines reported earlier have been seen in the present experiment. However, to our surprise, none of the γ rays exhibited the characteristic Doppler-broadened shape, hereby indicating that the state lifetimes associated with these transitions are longer than a few picoseconds. This result appears to indicate that the observed transitions do not correspond to a cascade of γ rays between superdeformed states. Moreover, the coincidence spectra also strongly suggest that at least some of the transitions are misidentified and belong, in fact, to the nucleus $^{190}$Hg, which is reached here through the ($^{24}$Mg, α 3n)reaction. It is conceivable that a thin-target experiment (as in the original measurement) would miss some of the essential experimental evidence for this assignment because of the presence of isomers in the various decay paths in $^{190}$Hg and $^{192}$Pb. In any event, these results lead us to question the assignment of a superdeformed band to $^{192}$Pb.

The analysis is at present concentrating on the yrast spectroscopy of this nucleus. In particular, level sequences built on a 12$^+$, 1.1-μs isomer and a $\sim$ 500-ns 9$^+$ yrast state have been established up to spins in excess of 20h. This work will become part of the thesis of A. J. M. Plompen.

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a.5. **Search for Superdeformation in $^{191}$Tl** (Y. Liang, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, T. L. Khoo, T. Lauritsen, F. Soramel, S. Pilotte*, L. L. Riedinger†, C. H. Yu†, J. Lewis†, and I. G. Bearden†)

A number of superdeformed bands have been observed recently in the Tl (Z = 81) isotopes $^{193-195}$Tl. From the current results on superdeformation in Hg nuclei, it appears that the superdeformation region ends for Z = 80 at N = 108. The superdeformed bands seen in the Tl isotopes are more weakly populated than their isotonic neighbors in the Hg nuclei and a question has arisen concerning whether the Tl superdeformed chain extends as low in neutron number as the Hg chain.

Thus far, two experiments have been performed at the Holifield Heavy Ion Facility at Oak Ridge National Laboratory to search for evidence of superdeformation in $^{191}$Tl. The first experiment utilized the $^{159}$Tb($^{36}$S,$^{4n}$) reaction at 165 MeV, and $\gamma$-ray coincidences were measured using the Spin Spectrometer in conjunction with 19 Compton-suppressed Ge detectors. The data yielded a candidate for a superdeformed band which consisted of seven transitions and which was populated with an intensity < 0.5% relative to the $^{4n}$ channel. The second experiment was undertaken in order to validate the existence of this proposed band. Two significant changes from the previous experiment were made in an attempt to improve the experimental conditions, namely: (1) the experiment was performed using the compact-Ge ball which measures 3-fold Ge coincidences with high efficiency, and (2) the $^{26}$Mg + $^{169}$Tm reaction was used instead of the previous sulphur-induced reaction. No evidence for the proposed SD band was observed in the data. However, since the reactions used to populate excited states in $^{191}$Tl were different in the two experiments, no definite conclusion could be made on whether or not the seven transitions initially observed were members of an SD band.

Recently, an experiment was performed at ATLAS on $^{191}$Tl using the Argonne-Notre Dame BGO $\gamma$-ray facility in an attempt to confirm the presence of the proposed SD band. This experiment was proposed at ATLAS, because the superior peak to background delivered by the ANL Compton-suppressed Ge detectors over that available at the Holifield facility allows one to identify more readily very weak $\gamma$ transitions in the coincidence data. The $^{159}$Tb($^{36}$S,$^{4n}$) reaction at 165 MeV was again used and approximately $100 \times 10^6$ coincidence events were taken. Preliminary analysis of the data not only confirms the presence of the SD band in question but also has yielded another SD band. This second band appears to be the signature partner of the initial band. The presence of the second band was predicted from theoretical considerations, and its identification brings the experimental observations for superdeformation in $^{191}$Tl in line with that of $^{193}$Tl and $^{195}$Tl, i.e. in all cases two SD bands are observed which appear to be members of a strongly coupled structure. This new data also extends the A $\sim$ 190 island of superdeformation to N = 110 in the Tl isotopes.

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The discovery of multiple superdeformed bands within a single nucleus has made it possible to investigate the microscopic structure of both the ground and excited states in the second well. However, a greater impetus for detailed studies of excited bands has been the unexpected discovery that several pairs of related bands have almost identical transition energies. The first reported cases consisted of the pairs $^{151}\text{Tb}^*$, $^{152}\text{Dy}$ and $^{150}\text{Gd}^*$, $^{151}\text{Tb}$ - the * denotes an excited superdeformed band - where transition energies in the pair were found to be equal to within 1-3 keV over a span of 14 transitions. Later, another similar pair $^{149}\text{Gd}^*$, $^{150}\text{Tb}$ was found. This implies that transition energies are equal to better than 3 parts in 1000. A related case of identical transition energies occurs in $^{153}\text{Dy}$. Here, two excited bands have been interpreted as signature partners and the averages of the transition energies in the partners reproduce the $\gamma$-ray energies in $^{152}\text{Dy}$ within 1-3 keV.

The first attempt at an explanation of this surprising phenomenon was presented recently by Nazarewicz et al. The interpretation is done within the framework of the strong coupling limit of the particle-rotor model. In this limit, the transition energies in an odd nucleus, relative to those in an even-even core, obey simple relations which provide a straightforward explanation for the $^{153}\text{Dy}^*$, $^{152}\text{Dy}$ pair. In the case of the three other pairs mentioned above, this explanation requires, in addition, that the pseudospin symmetry applies in the superdeformed minimum in order to obtain decoupling parameters which are exactly $a = \pm 1$. Indeed, within the strong coupling picture, for a decoupling parameter $a = \mp 1$, the two so-called signature-partner superdeformed bands in an odd-A nucleus form degenerate doublets, with the $a = 1$ case giving energies identical to those of the core, while the $a = -1$ case has energies midway between those of adjacent transitions in the core. A case where $a = -1$ has not been seen so far, although it is predicted by Nazarewicz et al. to apply to an excited superdeformed band in $^{151}\text{Dy}$.

A few years ago, we reported on the first superdeformed band in $^{151}\text{Dy}$ from an experiment performed at Argonne. As the excited superdeformed band(s) is expected to be much weaker in intensity, additional statistics appeared to be required to look for the band corresponding to the $a = -1$ decoupling parameter. The experiment was performed at the TASCC facility at Chalk River with the 8\* spectrometer consisting of 20 Compton-suppressed spectrometers and an inner array of 72 BGO detectors. We used experimental conditions similar to those of the earlier experiment, i.e. the $^{122}\text{Sn}(^{34}\text{S}, 5n)$ reaction at 175 MeV was used with two 500-\(\mu\)g/cm\(^2\) targets. The data of this experiment were added to the earlier ANL set in order to obtain a total coincidence matrix with an excess of $5 \times 10^8$ events.

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The analysis confirmed the superdeformed band reported earlier. At present, searches for a superdeformed band with transitions midway in energy to those of the superdeformed band in $^{152}{\text{Dy}}$ have not been successful. This result raises questions regarding the pseudospin picture. The analysis is continuing, with an emphasis on the strong ridge-valley structure that is in the $\gamma-\gamma$ correlation matrix.

a.7. **Rotational Bands with Identical Transition Energies in Actinide Nuclei**  
(I. Ahmad, M. P. Carpenter, R. R. Chasman, R. V. F. Janssens, and T. L. Khoo)

Recently it has been observed that transition energies in the superdeformed bands of nearby nuclei have almost identical energies within ~2 keV. It was believed that these identical bands occur only in superdeformed bands because of some special structure effects. We have now found identical bands in some even-even actinide nuclei. These occur in $^{240}{\text{Pu}}, ^{244}{\text{Cm}}, ^{246}{\text{Cm}},$ and $^{250}{\text{Cf}}$, and the transition energies are identical up to $I = 8$ (see Fig. IB-4). Spins higher than 8 are not known in these nuclei. However, high-spin states are known in $^{232}{\text{Th}}, ^{234}{\text{U}}, ^{236}{\text{U}}, ^{238}{\text{U}}, ^{240}{\text{Pu}}, ^{242}{\text{Pu}},$ and $^{248}{\text{Cm}}$ from Coulomb excitation studies. In these data, we find level energies identical in $^{236}{\text{U}}$ and $^{238}{\text{U}}$ up to $I = 24$; and the average value of this energy difference is less than 1 keV (see Fig. IB-5). This observation has led us to look for similarities in the level structures of the super-deformed Hg isotopes and the deformed U isotopes. We have performed calculations which show that in both cases there is a large gap in the single-particle spectra just before the region of identical bands. We have calculated the values of the alignment for the orbitals in the actinide region. We find that the orbitals $7/2-[7/2]$ and $1/2+[1/2]$, which are just above the gap in $^{236}{\text{U}}$ and $^{238}{\text{U}}$, have moderately large alignments but have opposite signs. However, since both orbitals are being occupied together, the net effect is a small alignment.

![Fig. IB-4. Known "identical" levels in ground state bands of $^{240}{\text{Pu}}, ^{240}{\text{Cm}}, ^{246}{\text{Cm}},$ and $^{250}{\text{Cf}}$.]
Fig. IB-5. A plot of energy difference, $\Delta E$, between the corresponding transitions of $^{236}\text{U}$ and $^{238}\text{U}$ against the rotational frequency ($\hbar \omega = 1/2E_\gamma$).

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The present status of research on superdeformation has been published as a review. The review discusses the various developments in this very active field of research which occurred since an earlier report by Nolan and Twin. Following an introduction, the discovery of a new region of superdeformed nuclei near $A = 190$ is discussed first. The present status of our understanding of superdeformation in nuclei near $A = 150$ is then summarized, and followed by a discussion on the discovery of bands with identical transition energies in neighboring nuclei of both the $A = 150$ and $A = 190$ regions. Effects related to possible octupole instabilities, neutron-proton interactions and weak pairing are also addressed. Finally, problems associated with the feeding and the decay of superdeformed bands are treated.

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We have measured the spin and (H,k) distributions associated with superdeformed (SD) and normal states in $^{192}$Hg populated at several beam energies with the $^{160}$Gd ($^{36}$C, 4n) reaction. (H refers to the sum energy and k the number of detectors which fire, before correction for the instrumental response). These data provide insight on how superdeformed bands are populated, as well as information on the mixing between excited superdeformed and normal states.

The spin distributions were derived from fold distributions in a 50-element BGO array, obtained by gating on appropriate lines in 12 Compton-suppressed Ge detectors. With respect to normal states, SD states have average entry spins ~6 $\hbar$ higher and appreciably narrower spin distributions. Comparisons of the high-$\ell$ edge of the different distributions reveal clear evidence for depletion of the highest partial waves due to fission.

The (H,k) distributions have been corrected for instrumental response and converted to (E,I) distributions, which represent the two-dimensional entry distributions leading to normal and SD states. (E and I denote energy and spin). Comparison of the entry distributions shows that the SD feeding originates from the higher partial wave portion of the total channel distribution. Furthermore, for each partial wave, the average entry energy for SD states is slightly lower than that for normal states. The SD entry distribution is well reproduced by model calculations we have performed (see B.a.10.). A paper on the results is being written.

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We have developed a model to follow the history of superdeformed states from formation to decay via Monte Carlo simulations. Both the feeding and decay of SD bands are governed by the mixing between SD and normal states and the electromagnetic decay rates in both the SD and normal wells. The mixing is, in turn, controlled by the tunnelling between the two wells and by the relative level densities in the two wells. The model can successfully reproduce all the observables connected with feeding of SD bands: entry distribution, intensity and variation of intensity with spin. Figure IB-6 shows the measured entry distributions for normal and SD states and the calculated distribution for SD states. The model shows that trapping into the SD well is decided near the barrier separating the SD and normal wells. Thus the feeding mechanism is now well understood, including the surprisingly large intensities of the SD bands.

Comparison of the experimental and calculated intensities and entry distributions lead to constraints on the energies of the SD band and on the SD well depth. This is important as there is as yet no experimental measurement on the energy of a SD band, although over 40 SD bands have been detected in the $A = 150$ and 190 regions. A paper is being written which compares the results of these calculations with those from our experiments.

![ENTRY DISTRIBUTIONS](image_url)

**Fig. IB-6.** Entry distributions associated with feeding of normal (experiment) and SD (experiment and model) states.
a.11. Calculations of the Decay of SD Bands
(T. Lauritsen and T. L. Khoo)

A typical SD band consists of 10-20 consecutive transitions which suddenly
terminate at low energy. The reason for the sudden decay out of SD bands into
normal states has not been well understood. Following Vigezzi et al., we
postulate that the decay occurs because of mixing between SD and normal states.
As the SD band decays, its excitation energy with respect to the normal yrast line
increases, so it is embedded in a dense sea of normal states, leading to some
mixing with these states. It is also important that the intraband E2 rate rapidly
decreases at low spin since the rate scales as $E^{-5}$ and the fractional decrease of
$E$ is large at low spin.

We have developed a model, following the method
of Vigezzi et al., to calculate
the decay out of SD bands in the $A = 150$ and 190 regions. The model is able to
account for the sudden decay and can also account for the fact that SD bands in a
given region decay out around similar spins. The spreading width $\Gamma$ of the SD
state among the sea of normal states turns out to be surprisingly small; for the $A = 130$
region it is a few percent of the average spacing between normal states, or
around 15 eV. The matrix element coupling SD and normal states is of the same
order. This nuclear matrix element is exceptionally small and reflects the small
probability for tunnelling between the SD and normal wells. The SD well depth $W_D$
can be inferred from the empirically deduced values of $\Gamma$ (with some assumptions)
and gives $W_D \sim 1.3$ and 1.9 MeV in the $A = 150$ and 190 regions, respectively, when
the SD bands decay at respective spins of $\sim 25$ and $10 \hbar$.


a.12. Search for the $\gamma$ Rays Connecting SD and Normal States
(T. Lauritsen, T. L. Khoo, E. F. Moore, I. Ahmad, M. P. Carpenter, R. V. P. Janssens,
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P. J. Daly*, B. Formal*, D. Ye†, and U. Garg†)

SD bands decay suddenly after a long series of cascade transitions. Yet not a
single pathway connecting SD and normal states has been delineated in the $A = 150$
and 190 regions. Thus, one concludes that the decay pathways are highly
fragmented, with each one too weak to be observed as a cascade of coincident
lines. The model described in Section a.11. ascribes the decay out of the SD band
to mixing with the normal states in which it is embedded. Thus, the spectrum of
decay $\gamma$ rays is simply that from an excited normal state, with excitation energy
above yrast of $\sim 4-6$ MeV. We have calculated this spectrum and, as expected, it
shows a statistical distribution.

We are attempting to isolate the corresponding experimental spectrum of decay $\gamma$
rays. The approach is to measure the total $\gamma$ spectrum coincident with SD band
transitions in Ge detectors. The major task is to disentangle these $\gamma$ rays from
those which preceded the population of the SD band. For $^{192}$Hg, the latter is
calculated to have a broad Gaussian-like E2 peak around 0.8 MeV, with a clear
dropoff at low energies. This E2 component is superimposed on a statistical tail
originating from decay towards the SD minimum. The experimental $\gamma$ spectra show an
additional component, located mainly below 0.6 MeV, which may arise from decay out
of the SD band. This preliminary conclusion needs to be confirmed by further
analysis, which is in progress.

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Recent data\(^1,^2\) suggest that the population intensities of superdeformed (SD) bands in $^{147}$Gd and $^{152}$Dy depend on the entrance channel used to produce the SD bands. For example, the SD band intensities in $^{152}$Dy are ~ 1% and 27% of the ground-state population in the $^{120}$Sn$(^{36}$S,4$n$)$^{152}$Dy and $^{74}$Ge$(^{82}$Se,4$n$)$^{152}$Dy reactions. It appears that the SD band is more favorably populated when nearly mass symmetric ions are used. Whether the increased population is due to the larger initial deformation of the compound nucleus after fusion or is due to the presence of higher partial waves in the spin distribution needs to be established. One expects a more diffuse tail in the $\mathcal{L}$-distribution for the mass-symmetric entrance channel. One way to ensure similar $\mathcal{L}$ distributions is to have fission impose the dominant cut-off in the high-$\mathcal{L}$ tail of the distribution. This can be achieved in the $A = 190$ region, where fission dominates beyond ~ 40%.

We have measured the entrance-channel dependence of the intensity of the SD bands in $^{191}$Hg using the $^{130}$Te$(^{64}$Ni,3$n$) and $^{160}$Gd$(^{36}$S,5$n$)$^{191}$Hg reactions at mid-target bombarding energies of 259 and 169 MeV, where $\mathcal{L}_{\text{max}}$ for both reactions are ~ 50%, well beyond the fission cut-off. The intensities of all 3 SD bands in $^{191}$Hg are 3.0 ± 0.8% and 3.7 ± 0.5%, respectively, of the $^{191}$Hg population. Thus, no enhancement in SD population is observed in the more mass-symmetric channel, unlike the effect in the $A = 150$ region. Our measurements do not prove that entrance channel effects are absent, but they emphasize that other effects than the entrance channel must also be considered. In particular, the SD intensity is extremely sensitive to the $\mathcal{L}$-distribution, since it originates mainly from the higher partial waves. In our reactions, $E(^{191}$Hg)$^*$ in the $^{64}$Ni reaction may be slightly higher by ~ 3 MeV since 2 fewer neutrons are evaporated, but similar excitation energy differences are also present in the reactions reported for the $A = 150$ region. In order to assess the effects of the entry distribution on the SD population, we have also measured the sum energy and fold distributions associated with population of normal and SD states in $^{191}$Hg. Figure IB-7 shows the measured average sum energies and folds in the $^{130}$Te$(^{64}$Ni,3$n$) and $^{160}$Gd$(^{36}$S,5$n$)$^{191}$Hg reactions are very similar. Thus, it appears that when the entry points are the same, mass symmetry in the entrance channel does not favor SD population in $^{192}$Hg. It would be desirable to measure the sum-energy and fold distributions also for the reactions in the $A = 150$ region to establish if the observed entrance channel dependence of the SD band population is due to differences in the spin distribution or to memory of the entrance channel.

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Fig. IB-7. Experimental entry points for normal-deformed (ND) and superdeformed (SD) states of $^{191}$Hg for the reactions $^{64}$Ni + $^{130}$Te and $^{36}$S + $^{160}$Gd.
b. **Shape Changes in Nuclei**

Research on the evolution of the nuclear shape as a function of spin and excitation energy along the yrast line and in its vicinity has concentrated mainly on nuclei in the $A \sim 190$ region; i.e. in the region where most of the superdeformation studies have been carried out. This region is of particular interest because as one gets close to the $Z = 82$ closed shell, the occupation of specific orbitals is expected to have a large effect on the overall nuclear shape. Furthermore, this region is one of the few where the cranked shell-model can be tested in the limit of oblate collective rotation ($\gamma = -60^\circ$, in the Lund convention). Our studies have concentrated on the yrast and near-yrast structures of the $^{188-191}$Hg isotopes, which involve mainly neutron excitations, and on proton excitations in $^{193}$Tl and $^{190}$Au.

In the past years, the attempt to investigate nuclear structure at higher temperatures has concentrated on properties associated with the decay of the compound nucleus such as (1) the competition between particle evaporation and $\gamma$ emission or (2) the detailed study of the quasi-continuum part of the $\gamma$-ray spectrum. Important ingredients of this aspect of the program are the calculations which attempt to simulate the decay of the hot nucleus within the framework of the statistical model. These simulations incorporate the latest theoretical ideas about the nature of the states at high excitation energy and spin. In particular, we have attempted recently to compare measured and calculated magnetic precessions for the pronounced E2 component of the quasi-continuum in $^{152}$Dy in order to gain information on the time evolution of this component of the $\gamma$-ray spectrum. A study is continuing on the spectral shape of the statistical component of the quasi-continuum spectrum in the case of an $(\alpha, 2n)$ reaction where collective components in the continuum are strongly reduced with respect to those observed in the usual $(HI, xn)$ reactions.

The focus of the research on reflection asymmetric shapes has changed from the new region of octupole deformation near $A \sim 146$ discovered at this laboratory some years ago, to the region near $^{222}$Th. Previous studies of $^{223,225}$Ac nuclei indicate that these nuclei are the most octupole deformed in their respective ground state. Since the largest octupole effects can be anticipated for odd-odd nuclei, a study of $^{224}$Ac has been initiated.

Finally, other aspects of the research program reflect major efforts by collaborators from outside institutions. These include (1) the study of a new region of deformation in neutron-rich nuclei near $A = 100$ from the spectroscopy of prompt fission $\gamma$-rays, (2) the study of the low spin structure of Po nuclei and (3) the study of quasi-particle excitations in neutron-rich Sn nuclei.
b.1. **Yrast and Near-Yrast Spectroscopy in $^{188,189}$Hg**


The data obtained in experiments designed to study superdeformation are usually of such quality that they allow for a very detailed study of all band structures in the nucleus under investigation. This was certainly the case for the nuclei $^{188,189}$Hg where such investigations have been carried out at ATLAS over the last two years. With the $^{156}$Gd($^{38}$S,4$n$)$^{188}$Hg reaction at 167 MeV and with the $^{160}$Gd($^{34}$S,5$n$)$^{189}$Hg reaction at 165 MeV, large $\gamma$-$\gamma$ coincidence data sets were obtained both with a stack of two 500-$\mu$g/cm$^2$ self-supporting targets and with a 1-mg/cm$^2$ target onto which a 15-mg/cm$^2$ Au or Pb layer had been evaporated. All data sets were taken with the Argonne-Notre Dame $\gamma$-ray facility and contain in excess of 10$^8$ events from which high multiplicity $\gamma$-ray cascades in the nuclei of interest can be extracted through suitable total multiplicity and sum-energy gating.

The level structure of $^{188}$Hg has been considerably expanded from earlier measurements$^1$ (see Fig. IB-8). Two distinct types of rotational structures emerge. One type is based on the groundstate and corresponds to the rotation of an oblate, collective nucleus ($\beta_2 \approx 0.15$, $\gamma = -60^\circ$, in the Lund convention). A total of 7 band structures have been associated with this shape. From the observed energies they all appear to be of rotational character. The other 3 band structures seen in $^{188}$Hg are associated with a prolate collective shape ($\beta_2 \approx 0.2$, $\gamma = 0^\circ$) which has been known for some time to coexist with the oblate structures at low and moderate spin. The analysis of these data is now complete and cranked shell-model calculations have started in order to try to understand the various band crossings seen in the data. $^{188}$Hg is one of very few nuclei where this model can be tested in both the prolate and oblate collective limits.

The level structure of $^{189}$Hg is currently still under analysis. While several new and interesting structures have already been discovered, there is still work to be done. Nevertheless, the following general statements can be made at this stage. Several of the observed sequences show rather regular patterns suggestive of collective rotation of a $^{189}$Hg nucleus with an oblate shape, while others display a more irregular pattern which might suggest a departure from axial symmetry. The situation appears to be quite analogous to that observed in previous studies performed on $^{190}$Hg and reported in earlier reports. We intend to perform total Routhian surface calculations in order to investigate the deformation space for this nucleus. These calculations will then become the starting point for detailed cranked shell-model calculations.

This experiment is part of the thesis work of I. G. Bearden.

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Fig. IB-8. Proposed level scheme for 188Hg.
b.2. **High-Spin States and Particle Alignments in $^{191}$Hg at Normal Deformation**


The level structure of the nucleus $^{191}$Hg has been extended considerably from previous studies by using the $^{160}$Gd($^{36}$S,5n) reaction. A series of 13 level sequences has been established in addition to three superdeformed bands. A majority of the band structures can be understood in cranked shell-model calculations assuming an oblate collective nuclear shape. There is some evidence for the onset of triaxiality. Two bands of single-particle character have been found. They are associated with a prolate, non-collective shape ($\gamma = -120^\circ$). A paper reporting the results has been published.\(^1\) This work is part of the thesis project of D. Ye.

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A recent spectroscopic study on $^{191}$Hg carried out by our group at ATLAS has shown that at moderate spin and excitation energy, non-collective structures compete in energy with the previously identified oblate rotational bands.\(^1\) This complexity of structure offered an excellent testing ground for cranked-Strutinsky calculations which make specific predictions of nuclear equilibrium shapes. The suggestion in the $^{191}$Hg work was that both neutron and proton orbitals are important in stabilizing the non-collective prolate shape in $^{191}$Hg. In order to study further the competition between collective and non-collective structures in this mass region, we have also established the near-yrast level structure in the odd-odd nucleus $^{190}$Au, an isotonic neighbor to $^{191}$Hg.

To populate high-spin states in $^{190}$Au, we utilized the $^{176}$Yb + $^{19}$F reaction at 97 MeV. The target consisted of three $350-\mu g/cm^2$ $^{176}$Yb foils and $\gamma$-ray coincidences were measured using the Argonne-Notre Dame $\gamma$-ray facility. In the data analysis, we have added significantly to the previously known spectroscopy of $^{190}$Au (see Fig. IB-9). At low-spin and excitation energy, the level structure is rotational in character. However, in the region where the first band crossing is expected, the level structure becomes fragmented and irregular. This phenomenon suggests that the non-collective states become yrast and dominate the level structure at a much lower frequency than observed in $^{191}$Hg, presumably due to the polarization effects of the odd proton. In order to make definite suggestions concerning the orbitals involved in the configurations for the single-particle states, an angular correlation analysis is currently being undertaken to establish firmly the spin and parity of the newly identified states.

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Fig. IB-9. Proposed level scheme for $^{190}$Au. Note that all spin values are tentative.
A recent spectroscopic study by our group on $^{193}{\text{Tl}}$ carried out at ATLAS has identified two superdeformed bands. Data from superdeformation studies are usually of such quality that one is able to improve on the information available for all states in a given nucleus. This appeared to be particularly useful in the case of $^{193}{\text{Tl}}$, since little was known of its yrast and near-yrast structure at moderate spin.

The data available for analysis came from two different data sets both using the $^{160}{\text{Gd}}(^{37}{\text{Cl}},4n)$ reaction at 167 MeV. The larger data set (200 x $10^6$ events) was taken using a thin target, and the smaller data set (10 x $10^6$ events) was taken with a thick target where all recoiling evaporation residues were stopped at the target position. The $\gamma$ decay of $^{193}{\text{Tl}}$ was measured using the Argonne-Notre Dame BGO $\gamma$-ray facility and the $^{37}{\text{Cl}}$ beam was supplied by ATLAS. In the off-line analysis, the relative yield of high-spin states in $^{193}{\text{Tl}}$ was enhanced by gating on higher BGO multiplicity (212). With this constraint, the $4n$ reaction channel was enhanced and represented approximately 80% of the 50 x $10^6$ events incremented in a $\gamma$-$\gamma$ coincidence matrix using the thin target data. Two major $\gamma$ sequences of opposite parity have been established from the data (see Fig. 1B-10). The negative-parity sequence has been observed up to a spin of $41/2^-$ and an excitation energy of 6.1 MeV while the positive-parity sequence has been extended to $I = 41/2^+$ and an excitation energy of 5.2 MeV. These two main sequences show markedly different level structure: the negative-parity sequence appears rotational in character while the level spacing in the positive-parity sequence is irregular and suggestive of a non-collective structure. The negative-parity sequence is initially yrast but is crossed by the positive-parity states at $I \sim 29/2^+$. 

These two band sequences have been interpreted in the context of mean-field calculations. In the theoretical analysis, we have made use of available total Routhian surfaces (TRS) calculations which have been performed using the cranked-Strutinsky formalism. These calculations classify the predicted nuclear equilibrium shape both as a function of quasiparticle configuration and of rotational frequency. Summarizing our interpretation of the level structure of $^{193}{\text{Tl}}$, the negative-parity sequence is identified as a rotational band built upon a high-$\Omega$ $h_9/2$ intruder orbital and having a near-oblate shape with a small quadrupole deformation ($\beta_2 \sim 0.15$). On the other hand, the positive-parity sequence is interpreted as a set of single-particle states corresponding to a near-spherical or perhaps a non-collective prolate shape. It should be noted that all these features are very similar to the properties found in the neighboring nucleus $^{191}{\text{Hg}}$ which has also been studied in great detail by our group. 

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Fig. IB-10. Proposed level scheme for $^{193}$Tl.
b.5. **Structure of the Odd-Odd Nucleus $^{224}$Ac** (I. Ahmad, J. E. Gindler, D. J. Henderson, M. P. Carpenter, E. P. Moore*, R. V. F. Janssens, T. L. Khoo, I. G. Bearden†, and C. C. Foster‡)

Our previous studies have shown that the odd Ac isotopes $^{225}$Ac and $^{223}$Ac are among the most octupole deformed nuclei. From theoretical considerations, it is expected that the addition of another unpaired nucleon to these nuclei will further enhance the octupole collectivity. For this reason, we have investigated the level structure of $^{224}$Ac by measuring radiations associated with the alpha decay of $^{228}$Pa ($t_{1/2} = 22$ h). The Pa activity was produced by the irradiation of $^{232}$Th with 45-MeV protons from the Indiana University Cyclotron. The Pa activity was chemically isolated from the target and thin sources of Pa were prepared for spectral measurements. Since the alpha branch for $^{228}$Pa is only 2%, gamma and electron spectra were measured in coincidence with alpha particles detected with high-resolution Si detectors. For gamma detection, a 231-Ge detector, a 2-cm$^2$ x 1 cm LEPS detector, and a Si(Li) X-ray detector were used. Electrons were detected in a 6-mm x 6-mm x 0.2-mm Si PIN diode operated at room temperature. In one case, an alpha-gamma-gamma triple-coincidence experiment was performed to establish the location of the levels. Although the alpha spectrum of $^{228}$Pa has been measured with a high-resolution magnetic spectrometer, the alpha group populating the $^{224}$Ac ground state has not been identified. In our experiment, we observe a 29.8-keV gamma ray in coincidence with the 6.129-MeV alpha group. We therefore give an energy of 30 keV to the level populated by this alpha group and all levels are assigned energies with respect to this level. We have constructed a level diagram consisting of several bands. However, since the ground-state assignments of $^{224}$Ac and $^{228}$Pa are not well established, it is not possible to uniquely identify the bands in $^{224}$Ac. We observe many low-energy E1 transitions which compete with the M1 and rotational E2 transitions. Also, two levels at 354 and 360 keV receive alpha population with low hindrance factors. We interpret these two levels as a parity doublet. These two levels decay to different levels near the ground state, further suggesting that they have opposite parities. Both the fast alpha transition to the 354-keV level and the presence of E1 transitions are characteristics of octupole deformation. We plan to perform high-resolution electron-spectroscopy experiments, both in coincidence with alpha particles and in coincidence with alpha particles and gamma rays, to establish the spins and parities of the levels.

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Structures of very-neutron-rich nuclei in the mass-100 region have been studied by measuring the prompt gamma rays emitted by nascent fission fragments produced in the fission of $^{248}\text{Cm}$. Gamma-gamma coincidence measurements were made with the Argonne-Notre Dame BGO gamma-ray facility which for this experiment consisted of 10 Compton-suppressed Ge detectors, two low-energy photon spectrometers and 50 BGO hexagons. From the analysis of the data we were able to identify transitions in several previously unknown nuclei and extend the level schemes of many known nuclei to higher spins. Transitions in $^{103}\text{Zr}$, $^{104}\text{Zr}$, $^{107}\text{Mo}$, $^{108}\text{Mo}$ and $^{105}\text{Nb}$ were observed for the first time. The level spacings in the ground-state bands of even-even nuclei provide information on deformation trends in the mass-100 region. In the odd-mass nuclei, single-particle states near the Fermi surface were characterized. The bands built on the $5/2^{-}[523]$ Nilsson state were identified in $N = 61$ and $N = 63$ nuclei. This observation points out the importance of the $h_{11/2}$ orbital in stabilizing the deformation in the mass-100 region. A paper summarizing these results has been published.$^1$

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b.7. **Time Evolution of the E2 "Bump" in $^{152}\text{Dy}$ Via Magnetic Precession Measurements** (N. Benczer-Koller, I. Ahmad, M. P. Carpenter, E. V. F. Janssens, T. L. Khoo, E. F. Moore, F. L. H. Wolfs, M. Hass*, G. Kumbartzki†, Ph. Benet†, and K. B. Beards§)

The time history of the E2 quasicontinuum peak in $^{152}\text{Dy}$ and the average g-factor of the excited continuum states have been studied. The method consists of observing the spin rotation in the enhanced transient magnetic field acting on the ions as they recoil through a magnetized Gd foil.

A Monte Carlo code, that has been very successful in describing the measured quasicontinuum gamma emission after particle evaporation, has been extended to also calculate the spin precession in a magnetic field as the cascade decays towards the yrast line. This model is used to interpret the precession observed in the experiment. The observed precession as a function of γ-ray energy also provides confirmation of the model used.

A paper on this work has been published.$^1$ Future experiments are planned in order to explore other time intervals.

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The decays of $\nu_{11/2}^n$ isomers in proton-rich $N = 82$ isotones have provided an outstanding illustration of the dependence of E2 transition rates between j$^N$ states on the subshell occupation number, and have demonstrated that half-filling of the $\nu_{11/2}$ subshell occurs just below $Z = 71$ ($^{153}$Lu). The counterpart $\nu_{11/2}$ subshell is being filled in the $A = 116-132$ Sn isotopes. In principle, one should be able to identify the $\nu_{11/2}^n$ excitations through this complete series of isotopes. Already $\nu_{11/2}^1$ 10+ isomers are known in 116,118,120Sn at one end, and in the fission products 128,130Sn at the other. Missing are 122,124,126Sn (with $N = 72-76$) for which theory predicts 10+ half-lives in the range 5-100 $\mu$s. These isomers cannot be produced in fusion-evaporation reactions because of the lack of target-projectile combinations. Encouraged by the results of our spectroscopy studies of inelastic and transfer processes populated in the $^{92}$Mo + $^{60}$Ni system discussed in earlier reports, we hoped that the Sn isomers might be identifiable through similar inelastic/transfer processes. Experiments have now been performed using pulsed $^{76}$Ge beams on 122Sn and 124Sn targets and the Argonne-Notre Dame BGO $\gamma$-ray facility. With the reaction 124Sn + 325 MeV $^{76}$Ge ($\sim 10\%$ above the Coulomb barrier), the decays of 10+ isomers in 120,122,124Sn were all clearly seen (Fig. IB-11), but no evidence was found for any excitation in 126Sn. Thus, two new 10+ isomers have been identified. In 122Sn, the half-life is 62(3) $\mu$s and the low-energy $\gamma$-ray associated with the decay has an energy of 75.2(5) keV. The same two quantities for the 124Sn isomer are: 45(5) $\mu$s and 78(1) keV.

These results establish the B(E2) minimum to be close to $N = 73$ and they provide the basis for theoretical comparisons of the $N = 82$ and $Z = 50$ series. While the half-filling of the $h_{11/2}$ neutron shell occurs near $N = 73$, the similar half-filling of the $h_{11/2}$ proton shell occurs just below $Z = 71$. This marked difference between protons and neutrons can be traced to the relative $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$ single-particle energies. For protons at $N = 82$ these orbitals are actually nearly degenerate, but for neutrons the $s_{1/2}$ state and, to a lesser extent, the $d_{3/2}$ come well below the $h_{11/2}$ state. These differences in single-particle energies are a consequence of the Coulomb potential, which for protons raises the $s_{1/2}$ and $d_{3/2}$ energies more than the $h_{11/2}$ energy. An enlightening comparison can also be made between the effective E2 ($e_{\text{eff}}$) charges observed in tin and lead isotopes. It is found here that $e_{\text{eff}}$ is about twice as large in the middle of the $N = 50-82$ shell as it is when the shell is essentially filled. It is striking that a similar conclusion had been reached earlier for the $N = 82-126$ shell from a study of $\nu_{13/2}^2$ states in the even-A Pb isotopes. Here too, the effective E2 charge more than doubles in the middle of the shell.

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These enhancements of $e_{\text{eff}}$ can be understood, at least qualitatively, as a consequence of additional configuration mixing, corresponding to polarization of the softer midshell core. An alternative, perhaps more conventional, explanation would be that 4-quasiparticle neutron admixtures cause the enhancement around midshell, where E2 excitations within the shell of the types $\nu g_{7/2} \rightarrow d_{3/2}$ and $\nu d_{5/2} \rightarrow s_{1/2}$ can build up low-lying E2 collectivity.

Relative cross sections for the population of the various $10^+$ states were also derived from the data. It is found that the $10^+$ levels in $^{124,120}\text{Sn}$ are populated 2.5 times less than the similar state in $^{122}\text{Sn}$, while the population of the $10^+$ isomer in $^{116}\text{Sn}$ is lower by a factor of $\sim 10$.

A publication reporting these results has been submitted. It emphasizes the spectroscopy aspects of the data, but information on the relative $10^+$ cross sections is also included. Few-nucleon transfer reactions in conjunction with high-sensitivity $\gamma$-$\gamma$ coincidence measurements show considerable promise for detailed spectroscopic studies of otherwise hard-to-reach nuclei. We plan to exploit this technique further in future experiments.

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**Fig. IB-11.** Off-beam $\gamma$-ray spectra for the reaction $^{124}\text{Sn} + 325$-MeV $^{76}\text{Ge}$ measured 2-80 $\mu$s after the beam bursts, with radioactivities subtracted. Spectrum a) is ungated while b) required a delayed BGO hexagon pulse 1-9 $\mu$s after the Ge detector signal. Random coincidence events are not subtracted.
b.9. 19/2+ Isomers in 119,121,123Sn (T. Lauritsen, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, Y. Liang, R. H. Mayer*, B. Fornal*, R. Broda**†, I. G. Bearden§, Z. W. Grabowski*, S. Lunardi†, and P. J. Daly*)

New long-lived isomers have been found in the odd-A Sn isotopes with A = 119-123 in the same experiments which provided the information on the 10+ isomers in the even Sn-A isotopes described in the preceding section. Sn isotopes with A > 120 cannot be studied by fusion-evaporation reactions, but were investigated here in off-beam studies following 122,124Sn + 325-MeV 76Ge collisions. For both targets, the off-beam spectra measured at the Argonne-Notre Dame γ-ray facility showed unknown γ rays decaying with 5-10-μs half-lives.

Six previously unassigned γ rays were found with energies 817.5, 837.5, 841.1, 1107.1, 1151.2, and 1220.0 keV. The coincidence data demonstrated that these six transitions should be grouped in pairs as follows: 818 and 1220 keV, 841 and 1151 keV, and 838 and 1107 keV. Within each pair, the γ rays were found to have similar intensities, to be coincident with one another, and to decay with a similar half-life. Moreover, the 838- and 1107-keV γ rays were both conspicuously absent from the spectra recorded with the 122Sn target, whereas the two other pairs still appeared strongly. The half-lives are 9.6 ± 1.2 μs for the 818-1220-keV pair, 5.3 ± 0.5 μs for the 841-1151 keV pair and 7.2 ± 2.6 μs for the 838-1107-keV pair. The 9.6-μs isomer is firmly assigned to 119Sn because a low-lying 1220-keV transition in this nucleus was identified in an earlier 116Cd(α,γ) study, and both the 818- and 1220-keV γ rays were previously observed at Legnaro in the 116Cd(7Li,p3n) reaction. The disappearance of the 838-1107-keV pair when 122Sn is used provides a forceful indication that these are transitions in 123Sn. This leaves the last pair to be assigned to 121Sn.

The energy systematics for the new isomers is presented in Fig. IB-12.

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Fig. IB-12. Energy systematics for even-A and odd-A Sn nuclei in the A = 116-124 mass range.
The three new isomers observed in the present work are interpreted by analogy with the known 1.75-μs isomer in $^{117}$Sn as $19/2^+$ states of $\nu_{11/2} \times 5^-$ character in the odd-A $^{119-123}$Sn nuclei, each of which decays to $15/2^-$ and $11/2^-$ states by a cascade of M2 and E2 transitions. The $15/2^-$ and $19/2^+$ energies follow closely the highly regular systematics of the $2^+$ and $5^-$ energies in the even-A isotopes. The identification of these $19/2^+ + 11/2^-$ sequences is a significant first step towards further studies of $(\nu_{11/2})^n, \nu = 3$ yrast states in these odd-A Sn nuclei. A paper reporting these results has been submitted for publication. A $7-7$ coincidence experiment of better statistics is scheduled to run in the near future in order to extend our knowledge of the yrast structure above the newly discovered isomers.

b.10. **Yrast States in Neutron-Rich Light Nuclei from Transfer Studies**


The analysis of lower multiplicity $\gamma-\gamma$ coincidence data from reactions of $^{34}$S, $^{36}$S, and $^{37}$Cl ions on $^{160}$Gd targets (used in the previous sections for superdeformation studies) has allowed us to identify reaction products where a few nucleons are transferred from the projectile and the target. In this way, $\gamma$-ray cascades in both the $A \sim 160$ and $A \sim 36$ regions have been identified. By placing coincidence gates on known $\gamma$ rays in the $A \sim 160$ products, individual reaction channels were selected and coincident $\gamma$ rays in the light partner products could be identified. The transfer of protons from the projectile to the target, with or without the exchange of neutrons, was found to be generally favored, leading to excited neutron-rich light nuclei. Some of the latter nuclei are difficult to reach by any other reaction and, as a result, new spectroscopic information was obtained. A striking feature exhibited by the data is the selective population of yrast states in these neutron-rich products. Gamma-ray cascades depopulating previously known yrast cascades have been observed in $^{32,34}$Si, $^{35}$P, and $^{36,38}$S. From the present work, new yrast sequences of $\gamma$ rays have been assigned $^{33}$Si, $^{34}$P, and $^{39}$Cl. Identification of new yrast states in these neutron-rich nuclei around the $N = 20$ shell closure offers an excellent possibility of testing cross-shell $sd$-$fp$ residual interactions.

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It has been predicted by Aberg that nuclei with mass 90-100 (e.g. $^{96}$Ru) exhibit collective rotation associated with a "dumbbell" shape. In order to test this prediction, an experiment was performed at ATLAS which populated excited states in the nuclei $^{96,97,98}$Ru using the $^{65}$Cu($^{36}$S,pxn) reaction at 135 and 142 MeV. The $\gamma$ decay of these nuclei were measured with the Argonne-Notre Dame BGO $\gamma$-ray facility. The $^{65}$Cu target had a thickness of 0.5 mg/cm$^2$ and was evaporated onto a Au foil in order to stop all recoils at the target position.

In the off-line analysis, no evidence for a rotational band associated with the predicted dumbbell shape has been found so far. The expected signature of this band would be similar to that for a superdeformed band, i.e. a dynamical moment of inertia which is large and nearly constant. However, we have established from the coincidence data gated on a BGO multiplicity $\geq 8$ two main band structures in both $^{96}$Ru and $^{98}$Ru extending significantly the previously known high-spin level structure. The $\gamma$ transitions observed in one of these two structures suggests that this sequence is rotational in character and co-exists with the near-spherical ground state.


We have measured the $\gamma$ spectra from $^{174}$Hf with the ($\alpha$,2n) reaction using beams from the Notre Dame FN tandem accelerator. The $\gamma$ rays were detected in an array consisting of 6 Compton-suppressed Ge detectors and 14 BGO hexagons from the University of Pittsburgh. There are two separate aims for this experiment. First, we would like to identify the non-yrast levels in $^{174}$Hf, in order to search for bands corresponding to multiphonon excitations. Second, we also want to extract the shape of the continuous statistical spectrum from the decay of $^{174}$Hf. The shape of this component of the spectrum gives direct information on the $\gamma$ strength function and on the level densities. It is preferable to measure the spectral shape of the statistical component using the ($\alpha$,2n) reaction instead of (HI,xn) reactions since the input angular momentum is not too high ($\ell < 14$) with $\alpha$-induced reactions. Thus, the E2 bump from continuum transitions preceding the discrete line decay (normally a dominant feature in reactions with large $\ell$) is quite small. After subtraction of the discrete lines one would be left with primarily the statistical spectrum.
This work is part of the thesis of L. Farris and the data are being analyzed at Rutgers. Analysis to determine the discrete levels is complete and the statistical spectra have been extracted. Calculations are now being performed, using different formulations of the level density, to compute the statistical spectra with a Monte Carlo code. The experimental spectrum can be well reproduced using a standard Fermi-gas formula for the level density. Work is in progress to explore the sensitivity to changes in the level density and, in particular, to search for any evidence for quenching of pairing with thermal excitation.


For nuclei near the doubly-magic $^{208}$Pb, the nuclear properties are dominated by the shell structure. However, as the neutron number decreases and approaches the middle of the shell, collective motion is expected to dominate. The neutron-deficient nuclei $^{199}$Po and $^{196}$Po have been studied by using the ATLAS facility at Argonne. The $^{176}$Yb($^{28}$Si,5n) and $^{172}$Yb($^{28}$Si,4n) reactions were used to populate the yrast and near-yrast states in this nucleus. Excitation functions were performed to determine different reaction products. From the $\gamma-\gamma$ coincidence measurements, the yrast states up to spin $\geq 29/2$ in $^{199}$Po have been established. The interplay of spherical shell-model and collective effects will be examined and the proposed level structures will be compared with the neighboring even-even and odd-A isotopes.

Analysis of both data sets are in progress. The work on $^{196}$Po will form part of the Ph.D. thesis of L. A. Bernstein at Rutgers University.

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C. ACCELERATOR MASS SPECTROMETRY (AMS) AND SECONDARY BEAMS

Around the world, AMS is primarily performed with tandem accelerators. This excludes the use of long-lived radioisotopes of noble gases ($^{39}$Ar, $^{81}$Kr, $^{85}$Kr) because they do not form negative ions. On the other hand, they are of great interest for geophysical investigations due to their inert character and their well-understood global distribution. Since the ECR-ATLAS system uses positive ions throughout, two years ago we initiated the development of AMS with noble-gas radioisotopes. At that time, an exploratory experiment with enriched $^{39}$Ar was performed which gave encouraging results for this novel development. The experiments will be continued as soon as the ECR positive-ion injector together with ATLAS becomes operational again.

Accurate half lives are the backbones of dating experiments with long-lived radioisotopes. We have finished a new measurement of the $^{41}$Ca half life which is in good agreement with two other values in the literature. We recommend the weighted mean of the three measurements as the most accurate half-life of $^{41}$Ca. We have also started a new half-life measurement for $^{44}$Ti, where a more accurate value is of particular interest for estimating $^{44}$Ti production in young remnants of supernovae, provided a signal from its decay can be detected with modern space-based gamma-ray spectrometers.

AMS for very heavy radioisotopes will be one of the future directions of AMS at ATLAS. Currently, we are investigating the production of the short-lived lead isotope $^{203}$Pb ($t_{1/2} = 2.2$ days). This radioisotope will be used to develop AMS for 15-Myr $^{205}$Pb, whose detection in a particular thallium mineral has been proposed as the only viable means to study the past low-energy solar-neutrino flux.

The development of short-lived secondary beams with the reaction H($^{17}$O,$^{17}$F)n, produced halfway through ATLAS, aims towards achieving conditions to perform secondary-beam experiments of interest to "hot" nucleosynthesis. Test experiments have revealed the conditions to be implemented in order to explore secondary-beam reactions.

a. **Half life of $^{41}$Ca** (I. Ahmad, W. Kutschera, and M. Paul*)

The half-life of $^{41}$Ca has been determined from a specific activity measurement of enriched calcium material containing 1.237% $^{41}$Ca. The activity was measured with a Si(Li) detector via 3.3-keV X-rays emitted in the electron-capture decay of $^{41}$Ca to $^{41}$K. From this measurement, a value of $t_{1/2}$ ($^{41}$Ca) = (1.01 ± 0.10) x 10^5 yr was determined.

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In order to obtain the most accurate value for the $^{41}$Ca half-life, we re-evaluated other measurements in the literature. In particular, we corrected the result of an activation experiment published in 1974 from its original value of $(1.03 \pm 0.04) \times 10^5$ yr to a new value of $(1.13 \pm 0.12) \times 10^5$ yr. This correction was caused by using adopted values of neutron-capture cross sections and by enlarging the systematic uncertainties to levels inherent to the method.

In 1991, a $^{41}$Ca half-life of $(1.03 \pm 0.07) \times 10^5$ yr was published, based on measuring the decay of cosmogenic $^{41}$Ca in Antarctic meteorites whose terrestrial age was determined from the cosmogenic $^{36}$Cl content. No corrections were applied to this value.

From the weighted mean of our result together with the other two mentioned above, we find $t_{1/2}$ ($^{41}$Ca) = $(1.04 \pm 0.05) \times 10^5$ yr. We recommend the use of this value for any work related to dating with $^{41}$Ca.

b. A New Half-life Measurement of $^{44}$Ti (I. Ahmad, W. Kutschera, G. Cini Castagnoli,* and M. Paul†)

Available values for the half-life of $^{44}$Ti range from 46 to 66 years, with deviations outside the uncertainties quoted for different measurements. We have started a new effort to re-determine this half life, with the hope of converging to the true half life of $^{44}$Ti.

A more accurate half life of $^{44}$Ti is of particular interest in connection with supernova SN1987A, since $^{44}$Ti may be present in young remnants of supernova. Gamma rays from 77-day $^{56}$Co have already been observed from SN1987A. When the shorter-lived activities have died, one hopes to find the activity of $^{44}$Ti with space-born gamma-ray spectrometers. Knowing both the half-life and the time elapsed since the supernova explosion, one can calculate the initial amount of $^{44}$Ti produced. $^{44}$Ti is also of interest for tracing cosmic-ray production in the 100-year range in recent falls of meteorites.

The new half-life measurement is performed by following the decrease of activity in mixed sources of $^{44}$Ti and $^{60}$Co with gamma-ray spectroscopy. The ratio of two characteristic gamma lines, $^{44}$Ti(1157 keV)/$^{60}$Co(1173 keV), together with the known half life of $^{60}$Co, should allow a very precise determination of the $^{44}$Ti half life. Three mixed sources containing 200 nCi of $^{44}$Ti and 200 nCi of $^{60}$Co each have been prepared and will be measured at three different laboratories (Argonne, Jerusalem, Torino).

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1W. Kutschera, I. Ahmad, and M. Paul, Radiocarbon 34, No. 3 (1992).
c. **Production of 2.2-day \(^{203}\text{Pb}\)** (W. Kutschera, I. Ahmad, M. Paul,* and B. Schneck†)

One of the unsolved questions in nuclear astrophysics is the solar-neutrino problem. Fifteen years ago a geochemical experiment was proposed\(^1\) to measure the solar-neutrino flux trapped in the thallium mineral lorandite (TlAsS\(_2\)) through the \(^{205}\text{Tl}(\nu, e^-)^{205}\text{Pb}\) reaction. Measuring the concentration of the long-lived radioisotope \(^{205}\text{Pb}\) \((t_{1/2} = 15\) million years\) in lorandite could provide, in principle, a measure of the past neutrino flux integrated over millions of years. One of the conditions for such an experiment is the development of an analytic method to measure the extremely small \(^{205}\text{Pb}\) concentrations. We are planning to develop AMS with the ECR-ATLAS system for this purpose.

One of the prime concerns in an experiment like this is contamination of the laboratory with unwanted quantities of \(^{205}\text{Pb}\). Therefore, we want to develop all aspects of the AMS method with the short-lived radioisotope \(^{203}\text{Pb}\) \((t_{1/2} = 2.2\) days\) rather than using enriched material of \(^{205}\text{Pb}\). Since thallium has two stable isotopes, \(^{203}\text{Tl}\) \((29.5\%\) and \(^{205}\text{Tl}\) \((70.5\%)\), we can also investigate the important question of isobar separation for the \(^{205}\text{Pb} - ^{205}\text{Tl}\) system using the \(^{203}\text{Pb} - ^{203}\text{Tl}\) isobar pair.

A possible way to produce \(^{203}\text{Pb}\) without any \(^{205}\text{Pb}\) is the reaction \(^{197}\text{Au}(^7\text{Li}, n)^{203}\text{Pb}\). However, a test experiment with \(^7\text{Li}\)-beam energies at 26, 30, and 34 MeV did not yield any detectable \(^{203}\text{Pb}\) activity. On the other hand, a strong \(^{201}\text{Pb}\) activity was observed indicating that the \(^{197}\text{Au}(^7\text{Li}, 3n)^{201}\text{Pb}\) channel was dominant. We have therefore produced \(^{203}\text{Pb}\) via the reaction \(^{197}\text{Au}(^9\text{Be}, 3n)^{203}\text{Bi}(11.8\text{h})\rightarrow^{203}\text{Pb}\) by irradiating a 156-mg/cm\(^2\) thick Au foil with 42-MeV \(^9\text{Be}\) of 44 nAh. This resulted in the production of \(5.6 \times 10^8\) atoms of \(^{203}\text{Pb}\). Mixing these atoms with 100 mg of stable Pb will give a \(^{203}\text{Pb}/\text{Pb}\) ratio of \(2 \times 10^{-12}\). Such isotope ratios are useful to develop the AMS technique for Pb isotopes. Due to the much smaller production path of the \(^{197}\text{Au}(^9\text{Be}, n)^{205}\text{Bi}(15.3\text{ d})\rightarrow^{205}\text{Pb}\) reaction, negligible amounts of (unwanted) \(^{205}\text{Pb}\) were produced. From the absence of any detectable \(^{205}\text{Bi}\) activity, we estimated a \(^{205}\text{Pb}/^{203}\text{Pb}\) production ratio of \(<2\times 10^{-6}\).

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\(^1\)M. S. Freedman et al., Science 193, 1117 (1976).
d. **Secondary Beam Development via the H(\(^{17}\text{O},^{17}\text{F})n Reaction** (W. Kutschera, D. Berkovits,† B. G. Glagola, R. C. Pardo, K. E. Rehm, J. P. Schiffer, B. Schneck,∗ M. Paul,† and T. F. Wang†)

Experiments with short-lived radioactive beams open new possibilities in nuclear physics. One of these experiments is nucleosynthesis in "hot" stellar matter, where the particle-induced burning of short-lived radioisotopes competes with their radioactive decay. A prerequisite for doing laboratory experiments in this field is the production of beams of short-lived species with sufficient intensity and proper energy. At ATLAS, we are using the inverse-kinematic reaction H(\(^{17}\text{O},^{17}\text{F})n to explore secondary beam production for the 1-min isotope \(^{17}\text{F}\). It is planned to eventually use this beam to study the reaction H(\(^{17}\text{F},^{14}\text{O})^{4}\text{He}, which is of interest for a "break-out" from the hot CNO cycle. For this, a \(^{17}\text{F}\) beam intensity in the range of \(10^6\) to \(10^7\) particles is required.

Our basic scheme is to produce \(^{17}\text{F}\) halfway through ATLAS at \(^{17}\text{O}\) energies of 80 to 90 MeV, where the production cross section is large (\(\sim 100\) mb). The second half of ATLAS will be used to decelerate \(^{17}\text{F}\) to energies around 40 MeV, where the secondary reaction will be studied. In test experiments \(^{17}\text{F}\) was transported through ATLAS and clearly identified in the split-pole spectrograph, at intensities of about 10 particles per second. However, these experiments revealed an inefficient cleanup from primary \(^{17}\text{O}\) particles. This residual \(^{17}\text{O}\) beam masks the secondary \(^{17}\text{F}\) particles to an extent which does not allow a detailed study of its properties. We thus plan to use the Fragment Mass Analyzer (FMA) for establishing cleaner conditions.

Due to reaction kinematics, both the transverse and longitudinal phase space of the secondary beam is much larger than the one for the primary beam. A production target between two strongly focussing superconducting solenoids followed by a superconducting rebuncher should allow one to shape the phase space in such a way as to fit it into the acceptance of the subsequent deceleration and beam-transport system. Extensive beam-optical ray-trace calculations have been performed which show that such a scheme is feasible. One of the crucial problems to be tackled next will be the development of a hydrogen target which can stand a tightly focussed beam of high primary-beam intensity. A rotating target wheel assembly will be tested as the next step in this development. Table I summarizes possible improvements where an optimized secondary-beam system is available.

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Table IC-I. Projected goals from the results of test experiments to investigate the secondary beam production of 64-sec $^{17}$F via the $\text{H}(^{17}_0,^{17}_F)n$ reaction between booster and ATLAS linac.

Primary $^{17}_0$ beam: $E = 90$ MeV
Secondary $^{17}_F$ beam: Mean energy = 75 MeV, Energy Spread $= \pm 5$ MeV, Angular spread $= \pm 31$ mrad (1.8 deg)

<table>
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<th>Parameter</th>
<th>Achieved</th>
<th>Hoped-for Improvement</th>
<th>Goal</th>
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<tr>
<td>$^{17}_0^{5+}$ beam</td>
<td>2.5 pnA</td>
<td>$10^3$</td>
<td>2.5 pμA</td>
</tr>
<tr>
<td>$(\text{CH}_2)_n$ target</td>
<td>905 μg/cm$^2$</td>
<td>7</td>
<td>1 mg/cm$^2$ H</td>
</tr>
<tr>
<td>cross section</td>
<td>100 mb</td>
<td>1</td>
<td>100 mb</td>
</tr>
<tr>
<td>fraction of phase space accepted for $^{17}_F$</td>
<td>$\frac{1}{200}$ (est.)</td>
<td>$10^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{17}_F^{9+}$ stripping fraction</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>transmission from target to spectrograph</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{17}_F^{9+}$ beam at spectrograph</td>
<td>11 pps (30 est.)</td>
<td>$7 \times 10^5$</td>
<td>$8 \times 10^6$ pps</td>
</tr>
<tr>
<td>Luminosity for $1$ mg/cm$^2$ $(\text{CH}_2)_n$</td>
<td>$1 \times 10^{21}$ cm$^{-2}$s$^{-1}$</td>
<td>$7 \times 10^5$</td>
<td>$7 \times 10^{26}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>reaction rate for $\sigma = 1$ mb</td>
<td>$1 \times 10^{-6}$ s$^{-1}$</td>
<td>$7 \times 10^5$</td>
<td>0.7 s$^{-1}$</td>
</tr>
</tbody>
</table>

a) Estimated from the geometrical acceptance of the 40-degree bending magnet.
b) Estimated counting rate from the quantities given above.
c) For a reaction on hydrogen, e.g. the $\text{H}(^{17}_F,^{14}_0)^4\text{He}$ reaction.
D. OTHER TOPICS

In addition to the research described in the previous sections some effort was devoted to other topics, mainly related to the behavior of cooled charged-particle beams. First experiments involving Li and Er beams at the Aarhus storage ring ASTRID have been performed and analyzed. In addition, simulation calculations of ions in a one-dimensional ion trap have been performed.

a. **Measurements at ASTRID with \(^7\)Li Beams** (J. S. Hangst,* P. S. Jessen,†
M. Kristensen,‡ J. S. Nielsen,‡ P. Shi,‡ O. Poulsen,‡
and J. P. Schiffer)

During 1991 further measurements were carried out at the ASTRID storage ring in Aarhus on the laser cooling of stored low-energy ion beams. The initial measurements of about \(10^9\) \(^7\)Li\(^+\) ions indicated very low longitudinal temperatures around 1 mK, corresponding to the lowest temperature ever reported in an ion beam. The problem with Li is that only the small isomeric fraction of the beam <<< 1\% is addressed by the laser cooling. Intrabeam interactions are not well understood. During the past year further measurements were carried out that indicate the transverse size (and temperature) of the beam was much higher than the longitudinal -- perhaps by as much as 6 to 7 orders of magnitude. This would imply small coupling within the beam. Further measurements with Li beams are planned during 1992.

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b. **Measurements at ASTRID with an Er Beam** (J. S. Hangst,* P. S. Jessen,†
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and J. P. Schiffer)

A beam of Er was injected into ASTRID because the 5416-A transition in Er is connected to the ground state, and thus 100\% of the beam should be visible to the laser cooling. However, the lifetime of this transition was not known and estimated to be on the order of 1-2 microseconds -- which may have been marginally sufficient. No laser cooling was observed with the Er beam and the lifetime was determined to be a factor-of-4 longer than the estimate -- comparable to the passage of ions through the interaction region. Thus an Er ion could absorb at most one photon per turn -- while for the Li beam several hundred per turn may be absorbed. The laser cooling force therefore is much weaker and apparently insufficient to overcome the intrabeam interactions. Plans are in progress for using other more favorable beams where 100\% would be accessible to laser cooling, but this requires additional hardware.

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c. **Beam-Size Measurements, Intrabeam Interactions, and Simulations**
(J. S. Hangst,* P. S. Jessen,† M. Kristensen,† J. S. Nielsen,† P. Shi,† O. Poulsen,† and J. P. Schiffer)

Beam size measurements were made using a slit, or beam scraper, that was gradually lowered into the beam while monitoring the longitudinal Schottky signal from the beam. Further molecular dynamics simulations have been carried out to get a better understanding of these measurements. While the simulations cannot be done directly for the large number of particles and high temperatures that characterize the experimental system, several valuable insights about the relevant parameters have been obtained.

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*Supported by the Danish Research Academy and Fermi National Accelerator Laboratory
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d. **Simulation of Cold Ions in 'One-Dimensional' Ion Traps** (J. Schiffer)

Recently Wineland et al. at NIST in Boulder have studied cooled ions in a trap where the radial confining force is much stronger than the one along the axis, in order to produce a one-dimensional configuration of ions that is particularly suitable for time standards. Molecular dynamics simulations have been carried out to better understand the limits of such one-dimensional configurations. With the ratio of the strengths of the radial-to-axial forces 100:1 (approximately the value used in the measurements) a linear configuration along the axis is possible up to 33 ions. For more than 33 the lowest energy static configuration involves some ions that are off-axis. For the ratio 1000:1 this increases to 91 ions, and after that seems to increase roughly with the square root of the number of ions.

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The possibility of performing direct reaction studies with light ions on nuclei away from stability has stimulated a proposal for an experiment for GSI, for the investigation of p,p (a,a') and (d,p) reactions on nuclei in the vicinity of the doubly magic isotopes $^{56}$Ni and $^{132}$Sn. Secondary beams now available from the heavy ion synchrotron SIS at GSI, in combination with the fragment separator FRS and the experimental storage ring ESR, are opening the possibility for such nuclear structure studies using the method of inverse kinematics.

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*GSI, Darmstadt, Germany
†University of Mainz, Germany
‡Technical University, Munich, Germany
§I. V. Kurchatov Institute, Moscow
As a first experiment we plan to investigate $p^\left(\text{\text{56}Ni},p'\right)$ inelastic scattering to the first-excited state at 2.7 MeV. Due to the favorable kinematical situation (large level spacing; insensitivity to beam-energy spread) and the reasonable $\text{56}Ni$ rates expected from presently available primary beam intensities, this reaction was chosen for a measurement directly behind the FRS without the ESR storage ring.

To test the experimental setup and to obtain information about backgrounds, $p^\left(\text{\text{20}Bi},p\right)$ elastic scattering at 100 MeV/u was investigated in a recent test run. The background originating from $\text{20}Bi + \text{12}C$ collisions was studied by comparing proton spectra from $(\text{CH}_2)_n$ and pure carbon targets; particle identification was done by TOF. Protons for the pure carbon target in the energy region $0 \leq E_{lab} \leq 8$ MeV amounted to only about 10% of the elastic rate from CH$_2$ and are most probably due to hydrogen contaminants in the carbon targets. Under these conditions a signal-to-background ratio better than 1:1 is expected for the $p^\left(\text{\text{56}Ni},p'\right)$ experiment, in particular since the proton energies will be higher for the $\text{56}Ni$ beam than for the $\text{20}Bi$ beam. Good agreement is obtained for the measured shape of the angular distribution of protons recoiling from a Bi beam, compared to optical-model calculations.

In addition to this study, test measurements using stored beams of stable isotopes ($\text{20}Ne$, $\text{40}Ar$) were performed at the internal ESR gas target with the aim to establish a luminosity monitor. Therefore elastic scattering near the grazing angle (close to 90° in the lab) was investigated. The observed count rate is consistent with an assumed gas-jet density of about $5 \times 10^{11}$ atoms/cm$^2$. After switching off the gas-jet a negligible background rate is observed. For a $\text{20}Ne$ beam hitting a $\text{14}N$ target a lifetime in the storage ring of $\tau \approx 100$ min was measured in good agreement with lifetime measurements performed with other methods.

**f. A New Concept for Measurement of the Electric Dipole Moment of the Neutron (M. S. Freedman, M. Peshkin, G. R. Ringo, and T. W. Dombeck*)**

The measurement of the electric dipole moment of the neutron (NEDM) is a crucial test of time-reversal invariance. The existing experiments fundamentally measure an energy or frequency shift in a nuclear magnetic resonance experiment. Using realistic projected values of electric field and the number of neutrons, the experimenters expect that a sensitivity of a few times $10^{-27}$ e·cm is the best they can hope to achieve. Any approach that basically measures an energy or frequency shift in a uniform electric field shares this fundamental limitation. The same is true of an ordinary Mach-Zehnder interferometry experiment with a uniform electric field $E$ in one arm of the interferometer so that the momentum $p$ in that arm is shifted by $\Delta p = \mu_e E / v$. Here $\mu_e$ is the NEDM and $v$ is the neutron velocity.

In anticipation that greater sensitivity may be needed, we have been exploring speculative new concepts for measuring the EDM by interference or polarimetry experiments using ultra-cold neutrons (UCN). In this approach neutrons are confined in an accelerator containing a strong electric field gradient and a guide field, both parallel to the horizontal x axis. The neutrons in the

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accelerator are polarized normal to the guide field, i.e. they are precessing around the guide-field direction. This is equivalent to a (coherent) superposition of two states of opposite polarization in the $x$ direction. Given a NEDM these two polarization states would be pulled apart minutely by the electric field gradient. Several possible accelerator designs have been considered. Of these, the most promising appears to be an open-ended box in which neutrons can be confined by reflection from a curved roof and thereby kept in the accelerating electric field gradient for some 5-10 minutes. Preliminary calculations indicate that such a device can retain a useful number of neutrons.

After this period, the neutrons are caused to fall about 50 cm under the influence of gravity and then to strike a 45° mirror so that their small separation in $x$ is converted to a small separation in height, hence a small separation in gravitational energy. The remainder of the experiment is similar in principle to the Colella-Overhauser-Werner gravity interferometer. The two beams acquire a phase difference proportional to their gravitational energy separation, which is proportional to $\mu_0$ but much greater than $2 \mu_0 E$, and can be detected within the limitation imposed by the uncertainty principle. The phase shift can be detected as a shift in transverse polarization when the two spin states are allowed to interfere after another 500 seconds. Our interferometer differs from a conventional one in that the two interfering wave packets are never separated by as much as one nanometer, so that some daunting technical problems are avoided.

While rather detailed studies have suggested that systematic errors do not pose insuperable problems we have recently encountered a problem in doing quantum-mechanical calculations of the UCN behavior more accurate than the usual approximations in neutron interferometry. We must decide whether this problem will require major modifications of the proposed measurement.
Considerable effort in the past year went into the installation and initial measurements with the Fragment Mass Analyzer (FMA), into the installation of APEX and into test measurements for GAMMASPHERE.

The installation of the FMA has been completed and various tests with α-sources and heavy-ion beams have been performed. It was demonstrated that the ion-optical properties of the FMA fulfill the design specifications. Mass resolution $M/\Delta M$ of $350:1$ have been measured for ions with masses up to $A = 150$. Excellent rejection capabilities for scattered beam particles were achieved using time-of-flight techniques between a parallel grid avalanche counter and a Si-detector. This improvement was essential for a first experiment studying the α-decay of nuclei far from the valley of maximum β-stability. Furthermore it was also shown that the FMA can handle inverse reactions, i.e. reactions where the rigidity of the evaporation residues is very close to the rigidity of the beam. The setup procedure for the ion-optical elements of the FMA has been greatly simplified by the use of a control computer which calculates and controls the required field settings for a particle with given mass, charge, and energy.

The main components of the APEX experiment have been installed at ATLAS. The coils for the solenoid and the vacuum vessel have been aligned and field mapping showed that the homogeneity of the magnetic field is within the specifications. First beam tests with $^{58}$Ni beams indicated good transmission of the beam line and a beam spot which was within the design specification for APEX. The major part of the 432 Si-detectors has been delivered and performance tests have been done. First experiments with sources in the APEX vacuum vessel have started. One of the barrel-shaped NaI arrays has been delivered to ATLAS and is presently being installed. The detectors for the second array have been delivered from the vendor and are being assembled and tested at Yale. First heavy-ion tests of the parallel-plate avalanche counters are scheduled for early February. All of the commercial electronics including the data-acquisition system have been delivered and tested. All custom-built electronic modules have been designed and delivery of the components is expected to be complete by the summer of 1992. First test experiments investigating questions about backgrounds and efficiencies have already begun.

The gamma-ray group at ATLAS has been very active in the GAMMASPHERE project. This includes tasks of administrative nature (e.g. chairman of the Scientific Advisory Committee) as well as tasks associated with the design and construction of the device. Two Compton-suppressed prototype Ge detectors have been tested at Argonne and an excellent suppression ratio of 0.68 $(P/T)$ was obtained. Within the GAMMASPHERE collaboration the Argonne group has taken on the responsibility for procurement of the BGO detectors. The bids are presently under evaluation. Argonne has also been strongly involved in the testing and optimization of the BGO-shields including the associated photomultiplier tubes. Other activities included investigations of ballistic deficit corrections via software and studies of the effect of neutron interactions in Ge and BGO crystals.

Other development projects at ATLAS include the construction of a large-area Si-detector array using double-sided Si strip detectors including the associated readout electronics. This array has a high efficiency for reactions with many particles in the outgoing channel and was used successfully in
several experiments studying the decay of exotic cluster states in light nuclei.

Investigations of the properties of a gas-filled magnet have continued including the construction of a x-y position-sensitive parallel-plate avalanche counter for the spectrograph, which will be used for the measurements of fusion excitation functions in heavy systems.


The FMA has undergone ion-optics tests with alpha particles from radioactive sources and beams from ATLAS. These have been extremely successful, demonstrating that ion-optically the FMA behaves as calculated. The FMA then was used in a first series of test measurements. Both fusion and transfer reactions have been investigated, in regular and inverse kinematics modes. Mass resolutions of 350:1 have been obtained for ions at masses 90 and 150, with broad M/q and energy acceptances as expected. Initially a Ge detector located at the target position was used to obtain recoil gamma-ray coincidences and thereby to establish the agreement between experimental and calculated positions for the masses on the FMA focal plane.

The 15" diameter general-purpose sliding-seal scattering chamber for the FMA target position has been installed and aligned. Beam tuning is accomplished using a small Faraday cup having a 2-mm diameter aperture, mounted in the target ladder. Stepping motors driven by the control computer are used to adjust the target position and angle, and the positions of two rotating rings. An aperture assembly immediately following the scattering chamber defines the FMA solid angle and holds a thin carbon foil used to reset the charge-state distribution of the ions before they enter the FMA. Design has begun on a small scattering chamber to be used with the Argonne-Notre Dame Compton-suppressed germanium detector array around the FMA target position.

A radiation safety interlock system has been designed and installed for the FMA. It relies on a series of redundant door switches, high-voltage power supply monitors, and fail-safe X-ray monitors. The electric dipole vacuum tanks have been covered with 0.25" lead shielding, including the lids, sides, and all ports. Surveys conducted during high-voltage conditioning indicate that this shielding successfully reduces external X-ray emission to a very low value.

Because of difficulties in field-locking over its entire range, the NMR system used to measure the magnetic field of the bending magnet has been replaced by a Hall probe. The control and monitoring program for the FMA now regulates the measured magnetic fields of the bending magnet and the quadrupoles by using the Hall probe sensors in a feedback loop.

Various detector configurations have been used at the FMA focal plane. The main detector for determining position is a thin parallel-grid avalanche counter (PGAC). This is followed by either a Bragg-curve spectrometer (built by the University of Notre Dame) or a silicon detector. Superb rejection of scattered beam at the focal plane has been achieved in a low cross-section implantation experiment by measuring the time-of-flight between the PPAC and a silicon detector placed 25 cm behind it. The moving tape collector (Iowa
State, Maryland, and LSU) has been completed, and will be tested with beam from ATLAS in the near future. Design work is continuing on the nuclear spectroscopy/nuclear moments facility behind the focal plane (Rutgers, Weizmann).

P. Sugathan, a student from the Nuclear Structure Facility in New Delhi, India has completed his 18-month assignment to the FMA project and has returned to his home institution. Graduate students K. Bindra (Vanderbilt University), and W. Chung (University of Notre Dame) are conducting Ph.D research on the FMA. Y. Nagame, from the JAERI laboratory in Japan, has returned to his home institution, after spending 14 months working on the FMA.

a.1. **Computer Control and Monitoring of the FMA** (C. Davids)

A computer program has been developed to monitor and control many of the FMA parameters. At the present time these include the magnetic fields, high voltages, and the scattering chamber, vacuum system, and support structure conditions. The program is written in Pascal, and runs on an Apple Macintosh IIcx computer. A major design goal for the program was to make the FMA easy to operate by the experimenter.

In order to set up the ion optics of the FMA, the user simply enters the energy, mass, and charge state of the central ion. The settings for the FMA power supplies are then obtained by the program from the master ion-optical solution for the FMA. If only the energy and mass are known, the most probable charge state is computed for the user. Parameter sets can be saved on a disk file for future use if desired. In addition, the computer periodically stores the various parameters in a log file for diagnostic purposes.

In the FMA, all electric and magnetic fields must be regulated to better than 0.1%. The computer is part of the feedback loop for the magnetic fields, using as input the measured values obtained from Hall probes attached to each of the 4 quadrupole singlets and the 40° bending magnet. The high voltages on the electric dipoles are controlled and monitored using 16-bit CAMAC ADCs and DACs. Communication between the various devices and the computer is by serial link.

Using stepper motors, the scattering chamber parameters such as target angle, position, and the orientation of the two inner detector rings can be set and read out easily.

An additional function of the FMA program is to perform automatic voltage conditioning of the high-voltage electrodes. The conditioning is done in the constant-current mode, in which just enough power is applied to keep the conditioning current at a safe value, typically a few tens of microamperes. With this algorithm the voltage increases steadily, and all adjustments to the operating parameters are made by the computer. During any spark episodes the power is automatically removed, and the voltage is then brought up again.


This detector, constructed at Notre Dame University, has been tested at the FMA focal plane. After undergoing several modifications, it is now in regular service at the FMA. Further tests are planned to determine the Z-resolution.

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a.3. **Moving Tape Collector for the FMA Focal Plane** *(C. N. Davids, J. C. Hill,* F. Wohn,* W. B. Walters,† and E. F. Iganjar†)*

The moving tape collector (Iowa State, Maryland, and Louisiana State) has been brought to ANL and instrumented for installation at the FMA focal plane. A system for detecting conversion electrons is being assembled at Louisiana State University. The tape collector will be tested with beams from ATLAS in early 1992.

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†University of Maryland, College Park, MD
‡Louisiana State University, Baton Rouge, LA

a.4. **Nuclear Spectroscopy/Nuclear Moments Facility for the FMA Focal Plane** *(C. N. Davids, N. Koller,* G. Goldring,† and M. Haas†)*

This facility will include a tilted-foil polarization apparatus which has been constructed at the Weizmann Institute and a magnet to be used in beta-NMR measurements. A surplus NMR magnet and power supply have been obtained. A test run with the FMA to determine the $^{43}$Ti production rate will be scheduled in the summer of 1992. The helium gas target for producing $^{43}$Ti is under construction.

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b. **The ATLAS Positron Experiment (APEX)** *(The APEX Collaboration - ANL, FSU, MSU, Princeton, Queen's, Rochester, Washington, and Yale)*

This experiment is designed to elucidate the origin of the narrow peaks observed in the spectra of positrons produced in collisions of very heavy ions with heavy nuclei. These peaks, first observed in experiments at GSI Darmstadt, have been the subject of a long series of heavy-ion and other related experiments. Despite this sizable effort, the nature and origin of the peaks remains enigmatic. The most pressing experimental question, as far as the heavy-ion experiments go, is a determination of the kinematics of positron-electron coincidence events to learn whether or not these events originate from the two-body decay of some unknown neutral objects. APEX data should allow the determination of the invariant mass of such hypothetical objects with a precision of 25 keV. In addition, the superior count-rate capabilities of APEX, as compared to previous experiments, will allow the investigation of many of the features of the phenomenon that have not been effectively covered by the work at GSI.

APEX is a collaborative effort between scientists at Argonne, Florida State, Michigan State, Princeton, Queen's, Rochester, University of Washington, and Yale. The current members of the collaboration are:

**Argonne:** I. Ahmad, B. Back, R. Betts,* R. Dunford, S. Freedman, M. Freer, T. Happ, W. Kutschera, J. Schiffer, P. Wilt, M. Wolanski,† and A. Wuosmaa

**Florida State:** J. Fox, and E. Roat†

**Michigan State:** S. Austin, E. Kashy, M. Maier, J. Winfield, and J. Yurkon

**Princeton:** F. Calaprice

**Queen's:** A. Hallin

**Rochester:** S. Gazes, A. Perera,† and F. Wolfs*

**U. Washington:** T. Trainor

**Yale:** K. Chan,† A. Chishti, P. Choudhury, J. Greenberg, N. Kaloskamis,† and K. Lister
The past year has seen much progress in the final assembly of the apparatus and its component detectors. Testing of many aspects of the experiment is currently well under way and, in some cases, completed.

The APEX apparatus consists of a 4-m long solenoid mounted transverse to the beam direction. Positrons and electrons produced at the target position in the center of the solenoid spiral down the field lines and are detected in highly-segmented, pencil-shaped silicon arrays placed close to the ends of the solenoid. Positrons are identified by measurement of their characteristic annihilation radiation in cylindrical scintillation arrays placed around the two silicon arrays. The angles of emission of both positrons and electrons are determined using a combination of energy and time-of-flight information. The status of the installation and testing of the major components of APEX is given below. It is expected that these tasks will be completed in time for the first positron experiments to be carried out when uranium and other heavy beams become available from ATLAS in Spring 1992.

*Project coordinators
†Graduate students

b.1. Solenoid and Vacuum Chamber (A. Hallin,* F. Calaprice,† B. Back, R. Betts, M. Freer, J. Schiffer, T. Trainor,† and A. Wuosmaa)

Following construction at Princeton, the APEX solenoid and vacuum vessel were delivered to Argonne in March 1991. The solenoid coils were installed and aligned, followed by installation of the vacuum chamber, vacuum and control systems. The solenoid coils were connected to the power supply which had been delivered in late 1990. A considerable effort was spent in developing techniques for field mapping using a computer-controlled 3-axis Hall probe which was positioned in the solenoid field using an Al guide tube. Following some initial difficulties with the guide-tube alignment and stability, a set of field maps were obtained for both the axial and transverse fields at several positions relative to the solenoid axis. The results of these measurements are consistent with the design plus earth's field with the addition of a transverse component due to magnetic material in the target area wall closest to the solenoid. The total field is within the specifications of APEX and any distortion of trajectories will easily be accommodated by the adjustments built into the positioning of the two silicon detector arrays. The vacuum system has been thoroughly tested and the base pressure reached is $<10^{-6}$ Torr. Work continues on refining the vacuum control systems and installation of many additional minor features to the mechanical and vacuum system. In essence, however, the solenoid and vacuum systems are complete and ready for operation (see Fig. IE-1)

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†Princeton University, Princeton, NJ
†University of Washington, Seattle, WA
b.2. APEX Beam Line (W. Kutschera, R. Betts, R. Dunford, J. Fox,* E. Kashy,† J. Schiffer, and J. Winfield†)

The APEX beam line in its original form was completed in early 1991. A number of tests of the functioning of the optical elements have been carried out during the past year using beams from ATLAS. One important question related to the effect of fringing fields in the switching magnet serving ATLAS Target Area IV which must run in saturation to bend the rigid U beams required for APEX. Measurements of the beam spot size and beam transmission were carried out using a beam of 300-MeV $^{58}\text{Ni}^{9+}$ which is closely similar in rigidity to the U beams for APEX. Initially, rather poor values were obtained for the spot size measured by looking at the beam transmission through various sized apertures. Fortunately, this problem was traced to the quadrupoles used in the APEX beamline which were of rather short design and had been obtained surplus from MSU. One of the two quadrupole doublets was replaced with a type commonly used at ATLAS. When further measurements were made using improved beam-spot diagnostics, very satisfactory results were obtained. We are now confident that U beams can be transported and focused as specified by APEX.

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†Michigan State University, East Lansing, MI
b.3. **Silicon Detector Array** (T. Happ, M. Freer, A. Wuosmaa, R. Betts, I. Ahmad, F. Calaprice,* and T. Trainor†)

The APEX experiment contains two arrays of silicon detectors positioned on the solenoid axis. Each array consists of 216 silicon detector elements, 3 x 0.5 cm² arranged on the surface of a hexagonal cylinder (see Fig. IE-2). These detectors provide information on the energy, time-of-flight, and impact position of positrons and electrons which strike the array after spiralling down the solenoid. The past year has been spent procuring and evaluating the production detectors and constructing and installing the mounting, readout, and cooling systems.

Following the evaluation of prototype detectors from two vendors, the APEX collaboration decided to split the total order equally between both suppliers.

One of the orders is complete, and the second should be so by the end of February 1992. In both cases, the delivered detectors all pass a stringent set of acceptance tests developed by us in consultation with the suppliers.

The mounting hardware and readout for one of the arrays has been fabricated and assembled, thus demonstrating the fundamental correctness of the ideas incorporated in the design. For the purpose of initial tests, this array has been installed in the solenoid with two rings (18 channels) of silicon detectors mounted. Initial source tests aimed at verifying the field alignment and solenoid transport properties are currently in progress. After we are assured that the array functions as desired we will proceed with fabrication of the second of the two arrays.

The cooling systems for the silicon arrays will be delivered shortly from the University of Washington. The silicon detectors in APEX will be cooled to -100°C so as to improve the energy resolution and charge collection for timing purposes. The cooling is accomplished by flowing cold nitrogen gas from liquid boiloff over the silicon detectors. The pressure in this system is 100 Torr, maintained by a thin Kapton shroud surrounding and separating the silicon detectors from the chamber vacuum. This system will be tested with the array in the APEX apparatus in February.

A source of electrons triggered by coincident photons has been developed for timing tests. A β-source is mounted close to a scintillator viewed by a phototube and can be placed in the center of the APEX solenoid. In this way the time of flight of electrons transported to the silicon array can be measured to verify the timing performance of the silicon array. This arrangement will be in use shortly with the partial array discussed above.

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†University of Washington, Seattle, WA
b.4. Sodium Iodide Array (K. Chan,* A. Chishti,* P. Choudhury,* J. Greenberg,* N. Kaloskamis,* and K. Lister*)

Positrons which strike the silicon arrays are identified by detection of their characteristic annihilation radiation by barrel-shaped arrays of position-sensitive sodium iodide detectors which surround each silicon array. Each barrel consists of 24 trapezoidal elements 55-cm long and 6-cm thick (see Fig. IE-3). The position sensitivity is achieved by treating the crystal surface to produce an exponential attenuation of the scintillation light as it propagates along the length of the crystal. Measurements of the light output at each end of the bar can then be used to reconstruct the hit position and the energy of the incident photon. This information, together with the azimuthal segmentation of the array is used to require a collinearity of two annihilation photons with a hit on the silicon array. In this way positrons can be clearly separated from the multiple electrons which are also produced in the heavy-ion collisions.

All of the bars have now been received from the vendor as well as the special mesh-dynode phototubes required for operation of the scintillators in the APEX field. One complete array has been shipped from Yale to Argonne and is currently undergoing tests together with the trigger processor (I.E.b.8). The second complete array is expected to arrive shortly. Following bench testing, the arrays will be installed in the APEX apparatus in two large lead-shielded carriages thus allowing the first tests of positron detection and identification with the silicon array.
b.5. **Heavy-Ion Array** (S. Austin,* E. Kashy,* M. Maier,* J. Winfield,* and J. Yurkon*)

The APEX heavy-ion array consists of 24 individual parallel-plate avalanche counters providing angle and time-of-flight information for scattered beam-like particles and recoiling target-like nuclei which strike the counter. In this way information on the masses and Q-values of the fragments formed in the positron-producing heavy-ion collisions can be obtained. These counters consist of low-pressure multiwire gas counters in which the position information is obtained from an anode fabricated as a meander-type delay line.

The production of the counters is almost complete. The complex gas-handling system and feedthrough ports have been delivered to ANL and are currently awaiting installation. A test of two counter modules with beam is scheduled for early February. Installation of the remainder will follow shortly.

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Fig. IE-3. The APEX annihilation detector array set up on a test bench at Yale.
b.6. **Target Assembly and Targets** (J. Fox,* E. Roa,* B. Back, and J. Greene)

In order to alleviate the problems of heating caused by the intense beams of U to be used in APEX and to reduce the effects of sputtering of target material, we have designed and constructed a rotating-target-wheel assembly. The assembly consists of a 5-cm-diameter wheel mounted on the end of a 1-m-long shaft driven at 400 rpm by an electric motor mounted outside the APEX vacuum chamber. The phase of the target-wheel rotation is sensed by a silicon photodiode readout system and this information is then used to chop the ATLAS beam whenever one of the spokes of the target wheel is in the way. An important feature of this target assembly is the ability to withdraw the target wheel and change targets without breaking the vacuum of the APEX vessel.

The complete assembly was delivered to ANL in summer 1991 and has been installed in the APEX vacuum chamber. It was used (non-rotating) in the beam-focussing tests during which the ability to transfer targets without breaking the chamber vacuum was demonstrated. The target rotation and beam-chopping mechanisms will be activated and tested in March 1992.

A dedicated target-making facility for U, Th and similar targets has been installed at FSU for APEX. This facility uses an electron beam-sputtering apparatus. Initially, targets for APEX will be fabricated at FSU. At some future time the facility will be moved to Argonne.

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b.7. **Electronics** (F. Wolfs,* P. Wilt, M. Maier,† E. Kashy,† and A. Perera*)

All of the commercial electronics have been received and tested and are now being installed in the experimental area. These items include high-power CAMAC crates, NIM Bins and racks, FERA ADC's, logic modules, a VME-based front end for data acquisition, fast amplifiers, high voltage supplies and distribution systems, and all cables.

The current status of the custom-built electronics is as follows.

A 16-channel constant-fraction discriminator has been designed, built, and tested, and will be produced for APEX by LeCroy. This production started in January 1992 and all modules will be delivered by the end of April 1992.

An 8-channel shaping module has been designed and evaluated. A low-level discriminator circuit and hit-pattern output will be incorporated in this design.

A low-noise preamplifier and time pickoff was designed and tested. This preamp can provide the necessary energy (7-keV) resolution and time (2-ns) resolution required by APEX. Production of these modules is now in progress.

A "motherboard" assembly for mounting the silicon preamps, containing all control and monitoring circuitry was designed and is currently being produced.

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A "peak-to-FERA" module to allow the use of FERA ADC's with silicon detectors and still give good energy resolution is being developed. It is probable that LeCroy will produce the modules for APEX.

Overall, it is likely that the production of the custom electronics modules will be the limiting factor in the operation of the complete APEX detector. We believe that delivery should be complete by summer 1992. In any case, initial running will be with only a subset of detectors and thus a lack of complete electronics should not impede progress.

b.8. **Trigger Hardware and Data Acquisition** (S. Gazes,* F. Wolfs,* J. Winfield,† T. Happ, S. Freedman, and M. Wolanski†)

A trigger module for APEX has been designed and fabricated. This device takes signals from the sodium-iodide arrays and, through a lookup process, provides triggers whenever back-to-back photons are detected in the array. This trigger will then be used in combination with logic from the accelerator and other APEX detectors to generate the electronics and data-acquisition gates. The trigger module is currently being tested with the sodium-iodide array.

As part of an upgrade of the Physics Division data-acquisition system, we procured and installed the hardware required for the operation of a front-end processing system developed at MSU. This new system uses VME modules and solves the problems caused by the obsolescence of the front-end processors currently used by DAPHNE. This hardware is installed and is being used in detector tests with APEX. In parallel with the introduction of the new hardware, the existing DAPHNE software was modified to run with the new hardware and is currently running at Rochester, where the APEX data-acquisition software has been written.

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*University of Rochester, Rochester, NY
†Michigan State University, East Lansing, MI
†Lab-Grad Participant, University of Chicago

**GAMMASPHERE Activities at Argonne** (T. L. Khoo, M. Carpenter, I. Ahmad, A. M. Baxter, M. Bleich,* R. V. F. Janssens, T. Moog, E. F. Moore, and P. Wilt)

A national gamma-ray facility consisting of 110 Ge detectors with BGO Compton suppressors is being constructed at LBL. After 18 months of operation there it will move to another site. 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) fold coincidences. Since each additional fold results in roughly an order-of-magnitude improvement in selectivity, this feature makes it possible to cleanly isolate weak structures, where new physics will undoubtedly lie. Since GAMMASPHERE represents a

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national facility, we are committed to participate in its construction. One of us is the Chairman of the GAMMASPHERE Scientific Advisory Committee (formerly Steering Committee) which follows, and provides advice on, the construction of GAMMASPHERE.

Through our activities in the Steering Committee, planning committees, and R&D, ANL has played a major role in securing funding for the project and in defining the instrument. Our GAMMASPHERE contributions include: (i) providing funds for purchasing prototype Ge and BGO detectors; (ii) procuring all prototype detectors; (iii) testing of all prototype detectors, including measurements of the combined performance of the Ge and BGO detectors as a Compton-suppressed spectrometer; (iv) developing software methods to correct for ballistic deficit and charge trapping at neutron-damaged sites in Ge detectors; (v) participating strongly in development of the detector configuration, electronics, computer hardware/software, and mechanical support design of GAMMASPHERE - for example we proposed the electronic-honeycomb design; (vi) continuing to suggest ways to improve the performance of GAMMASPHERE, e.g. to avoid the degradation due to neutrons and a segmented readout scheme for coaxial Ge detectors; (vii) participating in writing the GAMMASPHERE Baseline Review Document (May 1991) and the GAMMASPHERE functional requirements, which define the capabilities of the instrument; (viii) assuming all responsibility for the BGO detectors, including procurement, testing at ANL, and coordination of testing by university groups; and (ix) writing the software for implementing gain adjustments, ballistic deficit correction, event filtering (electronic-honeycomb suppression, neutron suppression, etc.). A paper on Compton-suppressed spectrometer performance has been accepted and one on ballistic deficit correction is being written. In addition, we have written four GAMMASPHERE Technical Notes (see I.E.c.11).


Each Ge detector in GAMMASPHERE will have a bismuth germanate (BGO) Compton-suppression detector system surrounding it (electronic honeycomb design). The BGO shield consists of a tapered hexagonal BGO side shield and one slotted BGO back plug.

Two prototype Ge detectors (see section E.c.3) and one prototype BGO Compton-suppression detector system (see section E.c.2) are available at ANL for evaluating the performance of the Compton-suppressed spectrometer. The BGO prototype represents the original honeycomb design where two adjacent Ge detectors share a common BGO shield. Tests for Compton-suppression using a 60Co source have yielded peak/total (P/T) ratios of: 0.24 (unsuppressed), 0.68 (suppressed), 0.62 (suppressed, no back-plug). Figure IE-4 shows unsuppressed and suppressed spectra; the additional suppression due to the back-plug is clear. The fully suppressed P/T is the best result reported so far for Compton suppression of a Ge detector. When a collimator is placed over the side-shield front face, the P/T decreases to 0.66 because of scattering of photons off the collimator into the Ge crystal.

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Figure IE-4. Plots showing the effect of Compton suppression on Ge detector spectra of a $^{60}$Co source. (a) Suppressed and unsuppressed versions of the same spectrum are compared. (b) Suppressed spectra are shown, with and without the backplug contributing to the suppression; these two spectra are normalized so as to have the same areas for the full energy peaks. (c) The ratio of the unsuppressed to the suppressed spectrum is shown, with and without the backplug contributing to the suppression. Spectra taken with backplug suppression are given in bold lines.

Many additional measurements on shield performance have been made in order to check Monte Carlo simulations and to indicate where improvements can be made. These tests can be summarized as follows. A study of the Ge-BGO energy correlations showed that in a coincidence between the Ge and BGO shield, the sum of the energy deposited in both the shield and Ge add up to the full energy 85\% of the time. This suggests that when energy resolution is not important, the Ge and BGO detectors may be operated in sum-coincidence mode to give excellent response with high efficiency. A measurement of the time correlation of BGO pulses relative to Ge pulses yields a time peak with a 20-ns FWHM. A study of the cross-talk between adjacent Ge detectors in the GAMMASPHERE arrangement showed that when $^{60}$Co $\gamma$ rays scatter between two adjacent Ge crystals, 2.2\% do not register a hit in the BGO shield. Despite the low transparency of the shield, this cross-talk can severely degrade the P/T ratio for coincidences between adjacent detectors in low-multiplicity experiments.
Ge-detector spectra, calculated using Monte Carlo simulations were used to develop and optimize the GAMMASPHERE design. These simulations predict substantially better performance for the prototype Compton-suppressed spectrometer (P/T of 0.79 vs. 0.68). An immediate concern is whether the poorer results obtained experimentally reflect some problem with the implementation of the design or result primarily from idealizations in the simulations. Our investigations have shown that the simulations must take into account γ rays which scatter from material near the source and Ge detector. When this was done, good agreement between the simulated spectra and measured spectra was obtained, indicating that the prototype is functioning as expected and that the simulations can predict performances accurately.

The same excellent P/T ratios should also be achieved in the current electronic-honeycomb design, where we propose to electronically combine signals from sectors of adjacent shields. Only if the two contiguous Ge detectors fire, the adjacent signals will not be combined, thereby reducing false vetoes. Thus the effective shield thickness remains essentially the same as that of our prototype. A manuscript reporting the results described above has been accepted for publication and the results are also reported in a GAMMASPHERE Technical Note.

c.2. Prototype BGO Detectors (I. Ahmad, M. P. Carpenter, T. L. Khoo, A. M. Baxter, R. V. F. Janssens, E. F. Moore, M. Bleich,* and I. G. Bearden†)

A prototype of the BGO Compton-suppression detector system, purchased with Argonne Laboratory discretionary funds, was tested at ANL. This prototype has the original honeycomb design where two adjacent Ge detectors share a common BGO shield. Results from the tests on the individual BGO elements of this prototype were reported in a manuscript accepted for publication and in a GAMMASPHERE Technical Note. These tests show very satisfactory BGO performance. For GAMMASPHERE, the electronic-honeycomb design was implemented where each Ge detector has its own BGO side shield, and the individual BGO elements are half the thickness of the corresponding elements in the existing prototype. A prototype BGO detector of the new design was built by Rexon and delivery is expected in early 1992.

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c.3. Prototype Ge Detector Tests (M. P. Carpenter, T. L. Khoo, A. M. Baxter, I. Ahmad, R. V. F. Janssens, E. F. Moore, M. Bleich,* and I. G. Bearden†)

Two prototype Ge detectors have been delivered by ORTEC and tested at ANL. The first detector, purchased with ANL discretionary funds, has a relative efficiency of 75%. Using a $^{60}$Co source, we found that the time resolution of this detector is 8.5-ns FWHM for $\gamma$ interactions depositing 300-1350 keV. The energy resolution of the detector for 1.33-MeV $\gamma$ rays is 2.23-keV FWHM when measured using an amplifier shaping time of 6 $\mu$s. The second Ge prototype, purchased with program funds, has a relative efficiency of 76% and the front face is tapered to permit larger BGO thickness for better suppression. The energy resolution of this detector was found to be 2.25-keV FWHM. Results from the tests on these two detectors are reported in a manuscript accepted for publication.

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c.4. Test of One-inch Diameter Photomultiplier Tubes on a GAMMASPHERE Prototype Segment (I. Ahmad, I. G. Bearden,* T. L. Khoo, M. P. Carpenter, and R. V. F. Janssens)

In the new individual BGO shield design for GAMMASPHERE, two one-inch diameter Hamamatsu R1924-10 photomultiplier tubes will be used with individual sectors of the BGO detectors. For this reason, we tested the performance of these tubes with a BGO sector (provided by REXON from the prototype they are constructing), using bases and preamps (provided by LBL) of the same type to be used in GAMMASPHERE. In the first test, both tubes were mounted on the crystal. With one tube powered and the other off, the resolution (FWHM) at 662 keV was 34%. When both tubes were powered, the signal increased by a factor of 2.0 and the resolution improved to 23%. In this mode, the peak-to-valley ratio for $^{241}$Am was found to be 13. The timing of this setup was also measured against a small BaF$_2$ crystal using a $^{60}$Co source. When the threshold was set at 4 keV, and the timing signal was derived from a leading-edge discriminator, the time resolution (FWHM) was 3.3 ns and FW(0.1M) was 6.7 ns for full-energy signals. The TAC was gated by the $^{60}$Co photopeak. When the threshold was increased to 8 keV, FWHM changed to 3.7 ns and FW(0.1M) to 7.2 ns. In the second test, we mounted only one tube at the center of the crystal face. With the tube directly coupled to the crystal, the resolution at 662 keV was found to be 29% and the signal was only 53% of the signal when both tubes were mounted. With a light guide the resolution became worse and was 30% at 662 keV. These measurements clearly demonstrate that for good light collection two one-inch tubes should be mounted on the BGO crystals. The tests reported here were performed with a crystal which was in the process of being prepared by the manufacturer. It is expected that the final version of the BGO crystal will give energy resolution specified for the GAMMASPHERE.
c.5. **Timing Measurements on GAMMASPHERE Prototype BGO Detectors**

(T. L. Khoo, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, and I. Bearden*)

The time resolution of the ANL/GAMMASPHERE prototype BGO detectors has been measured at several incident photon energies. The aim was to compare performance (full-width at half and tenth maxima, walk) using constant-fraction and leading-edge timing discriminators. (In the latter case, the trigger threshold was set at one and three times the single-electron noise level.) The widths were narrowest using leading-edge timing at the single-electron level for $E_\gamma > 450$ keV. Below that energy, constant-fraction timing yielded the best time resolution. At $E_\gamma = 1.3$ MeV, the full-width at half maximum (FWHM) = 2.4 and 3.2 ns with leading-edge (at the single-electron level) and constant-fraction timing, respectively. These represent excellent timing performance for BGO detectors and indicate that very good rejection of neutron interactions can be achieved (see I.E.c.7). The energy dependence of the FWHM was in excellent agreement with that calculated by Goulding and Landis and showed that the timing was governed by photon statistics. In all cases, the smallest walk was measured with constant fraction timing, as expected. We concluded that it would be satisfactory to implement BGO timing using leading-edge discriminators at the single-electron level, as planned for GAMMASPHERE. The larger walk using this method can be circumvented by setting gates on 2-dimensional time-energy histograms, instead of simple 1-dimensional gates on the time parameter.

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c.6. **Ballistic Deficit Correction of GAMMASPHERE Ge Detectors**

(M. P. Carpenter, T. L. Khoo, I. Ahmad, A. M. Baxter, R. V. F. Janssens, F. L. Wolfs, M. Bleich,* I. G. Bearden†, and D. Yet†)

The energy resolution of a Ge detector is limited by the charge-collection process when the shaping time of the amplifier is kept short (< 2 μsec) in order to keep pulse pileup at an acceptable level. This is a consequence of the finite charge-collection time associated with (i) interactions occurring in different parts of the detector (ballistic deficit) and (ii) charge trapping. This degradation in energy resolution is worse for larger detectors, such as those to be used in GAMMASPHERE.

Two methods have been developed to correct for ballistic deficit using hardware; they are referred to as the Goulding-Landis and Hinshaw methods. The first method applies a correction based on the crossover time, $\Delta T$, of a bipolar signal. The correction in the second method is derived from the amplitude difference $\Delta m$ of signals with different shaping times. We have implemented these correction methods using software and have also made improvements to the methods.

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A summary of our findings are: (1) for large n-type Ge detectors (80% and 74% relative efficiency), the Goulding-Landis method gave better resolution when the pulse-peaking time is 4 μsec or larger, whereas for shorter peaking times the Hinshaw method is superior; (2) software correction using a modified Goulding-Landis method equals or surpasses the improvement in resolution found using a commercially available module from ORTEC which performs a hardware analog correction; and (3) by combining both methods of corrections, we have developed a new method for separating events associated with neutron-damaged sites.

During the past year we have continued to develop and understand these correction techniques. For example, we have tested a shaping amplifier from Tennelec which performs the Hinshaw method internally. A comparison of energy-corrected spectra obtained using a software correction and the Tennelec amplifier show that the two methods are nearly equivalent above $E_\gamma = 1$ MeV, but the resolution at low energy is better with the correction made in software.

One other interesting result which came from this study is that the best resolution is obtained when a double correction is made, e.g. the Hinshaw-corrected spectrum is then further corrected using the Goulding-Landis technique. For example using a 75% Ge detector with a peaking time of 4 μsec, the uncorrected resolution for an 1836-keV γ-ray is 3.52-keV FWHM. After application of Hinshaw, Goulding-Landis, and combined methods, we obtained resolutions of 2.97, 2.92 and 2.87 keV, respectively.

During the past year, we have also applied our technique to the second Ge prototype for GAMMASPHERE. This was done in order to see how the parameters used for the correction vary between detectors. Ultimately, we would like to measure these correction parameters for a subset of the GAMMASPHERE detectors (~20). This information will enable us to determine how best to apply both the correction factors and the masking of neutrons. The implementation of this technique into GAMMASPHERE is one of our ongoing contributions to this project.

Results of our study on ballistic deficit correction have been reported in a GAMMASPHERE Technical Note and a paper is being written.
We have studied the effects of neutron interactions in Ge and BGO detectors on GAMMASPHERE performance and proposed methods to minimize the degradation. Neutrons cause several deleterious effects in $\gamma$-ray arrays: (i) radiation damage in Ge detectors; (ii) degradation in peak/total ratio ($P/T$) due to low-energy "tails" in the peaks after neutron damage of Ge detectors; (iii) degradation in peak/total due to the recognizable broad (high-energy-skewed) neutron lines and recognizable continuum interaction from inelastic neutron scattering in Ge; (iv) energy summing in Ge detectors when a neutron interaction deposits energy, adding to that due to a $\gamma$-ray interaction occurring $\sim 10$ ns earlier; (v) false veto of an otherwise full-energy event (i.e. with no Compton scattering) in the BGO suppressor; and (vi) contamination of $\gamma$-multiplicity and sum-energy spectra.

The deleterious effect of (i) has been widely recognized, but that is not always the case with (ii)-(vi). The cumulation of effects (ii)-(v) is very large, particularly in n-fold Ge coincidences, where the GAMMASPHERE resolving power is proportional to $(P/T)^n$.

Performance degradation due to effect (ii) can be overcome in a method we have proposed which uses the signals intended for ballistic deficit correction (see I.E.c.6). Degradation due to effects (iii)-(vi) can be minimized by time-of-flight rejection of neutrons, which arrive $\sim 10$ ns later than $\gamma$ rays. Clearly, the best rejection is achieved using the narrowest gates possible. The time resolution of both Ge and BGO detectors decreases with energy and there is also a variation (walk) of the centroid position with energy. Thus, the narrowest gates can be achieved with a 2-dimensional mask on a time-energy histogram to suppress neutron events. We propose that this suppression be implemented in the filtering process in the GAMMASPHERE front-end computers. This recommendation is incorporated, in a GAMMASPHERE Technical Note.

Within the GAMMASPHERE collaboration, it is the responsibility of the Argonne group to procure all the BGO shields for the facility. During the last year we devoted substantial effort to this activity. An advanced procurement plan was developed and requests for quotations were prepared and sent to potential vendors. Bids were received and are currently under evaluation. Placement of orders is anticipated to occur in March of 1992. First detectors are scheduled for delivery in early summer.
c.9. **Testing of the BGO GAMMASPHERE Detectors** (M. P. Carpenter, I. Ahmad, R. V. F. Janssens, and T. L. Khoo)

GAMMASPHERE, the national γ-ray facility, when completed will consist of 110 Compton-suppressed Ge detectors. Due to the geometry of the array, four types of annular shields will be required. These types are referred to as A, B, C and D and the array will consist of 12, 60, 30 and 20 of these units, respectively. Type A shields which have a pentagonal geometry are not included in the initial design. Shield types B, C and D have a hexagonal geometry.

It is expected that approximately 30 of the units will be delivered by the end of 1992 so that they can be used in the early-implementation phase of GAMMASPHERE operation in early 1993. Testing of the units will take place at several sites, namely, ANL (50 det., including 20 which will be tested by Notre Dame), Stony Brook (30 det.) and Yale (30 det.), and will be coordinated by ANL physicists. A set of test procedures has been developed in order to insure that all units meet the required mechanical and performance specifications. We are also upgrading our detector laboratory with the installation of a CAMAC-based acquisition station so that these tests can be performed efficiently with dedicated electronics. One aim of these tests is to provide the collaboration with a detailed test sheet for each BGO shield.

c.10. **Coaxial Ge Detector with Segmented Readout for Improved Resolution in Experiments with FMA and GAMMASPHERE** (T. L. Khoo, I. Ahmad, M. P. Carpenter, and R. V. F. Janssens)

When γ rays are emitted from a fast-moving nucleus (such as those tagged by the FMA), the Doppler effect broadens the line shape, particularly at angles near 90° where most detectors are located, so that the line width is usually wider than the intrinsic width (typically 2.2 keV at 1.3 MeV) by a factor of two or more. For example, with a recoil velocity of 0.04 c, the Doppler broadening would give 9.1 keV at 90°, or about 4.1 times the intrinsic resolution of the detector. Reducing the subtended angle by half would reduce this to 2.5 times the intrinsic width, and reducing the angle to one-third could bring the resolution to 1.9 times the intrinsic one.

We proposed a simple and elegant solution to reduce the subtended angle of GAMMASPHERE detectors, which is to segment the readout electrodes of coaxial Ge detectors. Such detectors, which can be made to be fully compatible with GAMMASPHERE, could then constitute detectors around 90° to upgrade its performance, and still leave the BGO shield configuration intact. The resolving power of n-fold γ-ray coincidence scales as \((\text{resolution})^{-n}\). Thus, in a large class of experiments with GAMMASPHERE, where typically 4 Ge detectors are required to fire \((n = 4)\), segmented readout will improve the resolving power by a factor of 10-20.

We hope to acquire funds to develop such a detector. The improved resolution of the segmented detector is particularly effective in experiments where the FMA at ATLAS and γ-ray detectors are used together, since the reaction products will always be recoiling at high velocity.
Segmentation of the electrodes was performed successfully on Si and planar Ge detectors, but has not been attempted on coaxial Ge detectors. For a coaxial detector, our idea is to divide the detector electrodes into two halves. The outer p-type contact can be subdivided during the boron implantation process, or a shallow groove can be cut after implantation. Alternatively, the inner contact can be subdivided by cutting a groove to separate the lithium-diffused contact. However, since the lithium migrates during annealing (required periodically to repair neutron damage), the long-term separation of this contact is a question. The decision on which contact to segment will be made after intensive consultation with the manufacturer.

Monte Carlo calculations would be performed to assess the extent that one can determine which half received the initial photon hit - reflected in larger energy deposition. After construction, the detector will be tested with collimated sources to determine the extent to which we can characterize correctly the half with the initial hit.

d. **Status of the Argonne-Notre Dame BGO Gamma-ray Facility at ATLAS**


The gamma-ray facility at ATLAS consists of (a) a 4π gamma-sum/multiplicity spectrometer with 50 BGO hexagonal elements (inner array) and (b) 12 Compton-suppressed Germanium detectors (CSG) external to the inner array. During the past year, the effort related to this facility has continued on several fronts:

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

-- Because of neutron damage, annealing was performed twice on eight detectors. For three detectors, the annealing was not successful and the detectors were returned to the manufacturer for further repair. In one case the problems appeared to be with the preamplifier stage located inside the vacuum in the cryostat. In the other two cases, the crystal itself had to be taken out of the cryostat and reprocessed. The reasons for these failures could not be determined with certainty, although we note that all these detectors are among the oldest in the facility and an aging process may be a factor. Because of the availability of spare detectors, the facility was able to run all the experiments with the full complement of 12 CSGs.

-- Maintenance and repairs had to be performed on several electronics modules and on the power supply of a CAMAC crate. None of these problems compromised an experiment.

-- A special reaction chamber designed for the detection of fission fragments was constructed. This chamber fits inside the BGO array and houses two large, position-sensitive strip detectors.

-- Preparations for the use of the CSGs at the FMA have continued with the following activities:

--- University of Notre Dame, Notre Dame, IN
--- Purdue University, West Lafayette, IN
--- Vanderbilt University, Nashville, TN
(1) the support which allows 10 CSGs to be placed around the target location of the FMA has been assembled and is now ready for use.

(2) a small target chamber suitable for use with the CSGs is being designed. Special attention is devoted to the specific requirements of minimal mass from which γ rays can scatter, the availability of a reset foil to equilibrate the charge-state distribution of nuclei recoiling in the FMA (in the event that isomeric states are fed in the reaction), the possibility to move the FMA at small angles of 0°, etc.

(3) procurement has been initiated for some elements of the BGO electronics which will be duplicated from the existing facility.

e. **The Argonne Silicon-Strip Detector Array** (A. H. Wuosmaa, R. R. Betts, B. B. Back, and P. Wilt)

Many nuclear physics experiments benefit from the ability to fully characterize the kinematics of final states consisting of several charged particles. Some examples include the study of nuclear-structure effects in the breakup of alpha-particle sd-shell nuclei following inelastic scattering and transfer reactions, as well as other inelastic scattering processes leading to highly-excited, particle-unbound states. In order to study these reactions with high efficiency, and in order to obtain enough kinematic information to completely characterize multi-particle final states, highly-segmented, high-resolution detectors are required.

We have constructed a large-area detector array to measure these and similar processes with high efficiency and excellent energy resolution. The array consists of four double-sided silicon strip detectors (DSSDs), each 5 x 5 cm² in area, with front and back sides divided into 16 strips. The detectors are thus effectively segmented into 256 pixel regions within the 5 x 5 cm square. If each of the strip-detector segments can be read out independently, x-y position sensitivity can be achieved for events in which more than one particle strikes the detector at a time. To fully exploit these capabilities, a system to read out each strip detector segment has been designed and constructed. The heart of the system is a custom multi-channel preamplifier constructed using integrated circuits which each provide eight channels of FET preamplifier. The preamplifier units themselves contain two of these integrated circuits, as well as 16 channels of custom-designed time-pick-off circuitry, packaged within one single-width NIM module. The necessary 32 channels of energy and time preamplification for each strip detector are thus contained within two single-width NIM modules.

The remainder of the system consists of high-density CAMAC modules, including multi-channel discriminators, charge-sensing ADCs, and time-to-digital converters (TDCs). As such, the total system is highly modular and compact, while remaining relatively low-cost. Using this system, energy resolutions as good as 25-30 keV have been obtained for 6-MeV alpha particles. Several successful ATLAS experiments have now been conducted using this array, in configurations utilizing two DSSD's with 64 electronics channels, and four DSSDs, with a total of 128 electronics channels. From these experiments, time resolutions of less than 500 ps have been obtained for particle energies greater than 20 MeV.
We also plan a number of improvements to both the detector array and readout system to further improve its flexibility, compactness, and modularity. One improvement is to increase the segmentation of the DSSDs themselves. There are several advantages to increased detector segmentation. Obviously, the position resolution of the DSSD is increased, providing better angle resolution for experiments relying upon reconstructed excitation energies derived from particle energies and angles. Also, since the area of each detector segment is smaller, the performance of each segment is improved due to smaller capacitance and per/segment leakage current. Finally, for many-particle events, the higher segmentation reduces the number of events that must be rejected due to more than one particle hitting a single strip. Of course, in order to operate more highly segmented detectors, additional electronics channels are required. The present modular form of the readout system makes it simple to add additional detector channels. We are presently exploring possible options for increased detector segmentation, with an eye toward balancing the higher cost of more electronics channels with the potential improvement in array performance that could be obtained.

A further addition to the present array design is to add detector elements for fast vetoing of events in which high-energy light particles penetrate the DSSD. In a recent experiment, a large number of uninteresting events involving high-energy alpha particles punching through the DSSD were recorded to tape. To alleviate this problem, a simple veto detector, consisting of a low-cost, large-area, low-segmentation detector, could be placed behind the primary strip detector. Events giving a signal in this veto counter could then be easily rejected. For low-multiplicity events, the front DSSD, with a present thickness of 500 microns, could be replaced with a much thinner device, thus providing a very-large-area, X-Y position-sensitive E-DE telescope.

Finally, many of the properties of this detector array and readout system are suitable for a high-density silicon detector array to be used in conjunction with other experimental apparatus. For example, GAMMASPHERE offers the opportunity to perform detailed, high-resolution particle-gamma-ray coincidence measurements with unprecedented efficiency. In order to take full advantage of these capabilities, a compact, flexible, high-density particle-detector array could be inserted into the GAMMASPHERE scattering chamber. With a variety of detector thicknesses available, a device similar to the present DSSD array could be used for such experiments, either for light, or heavy charged-particle - gamma-ray coincidence measurements.
Investigations to use a gas-filled magnetic spectrometer for Z-identification at low velocities have continued. The data obtained with 0.6-1-MeV/u $^{58}$Fe/$^{58}$Ni, $^{76}$Ge/$^{76}$Se, and $^{96}$Zr/$^{96}$Ru ions have been completely analyzed and strong variations of the resolution $Z/\Delta Z$ for the three systems have been observed. While $Z/\Delta Z$ was 32 for $A = 58$ it dropped to $Z/\Delta Z = 19$ for $A = 76$ and increased again to 34 for $A = 96$. A paper with the results of these measurements was published. To get a better understanding of the strong $A$-dependence we have started to simulate these results in Monte Carlo calculations with the code RAYTRACE which was modified to include charge-changing collisions in a gaseous medium. The code was also modified in order to run on an IBM RISC workstation. First calculations which include shell effects in the capture-and-loss cross sections have been started. The same Monte Carlo code was also used to simulate the measurements of fusion cross sections for heavy systems in a gas-filled spectrograph.

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We have started a program to measure excitation functions of fusion yields using a gas-filled spectrograph. Normal $\Delta E-E$ techniques are limited by the count rate the detectors can handle. We have built a parallel-grid avalanche counter (PGAC) for the focal plane of the Enge split-pole spectrograph which was optimized for fusion measurements. It has only one entrance foil which the particles have to penetrate, an increased vertical acceptance and a divided anode which allows the detection of elastically scattered particles and evaporation residues independently in the two halves of the detector. The new PGAC was tested with $\alpha$-sources and with $^{32}$S ions from the ATLAS accelerator. A comparison of the fusion cross section for the system $^{32}$S + $^{64}$Ni which has been measured previously by two different groups showed good agreement with the earlier measurements. A first experiment for the system Ni + Mo is planned for the spring of 1992.

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The VAX-780, which served as the hub for Divisional computing for about eight years, was replaced with two VAX 3300 computers during the first part of 1991. A replacement was necessary because of the high maintenance costs and low performance of the VAX-780 compared to more modern machines.

The Division has two VAXstation 3200, three VAXstation 3100 machines, and a MicroVAX II which operate as part of a VAXcluster with the two VAX 3300s as the boot servers. All of the satellite machines have local disks of about 600MB for paging, swapping, and user files. The two VAXstation 3200 have 8-mm tape
drives. The MicroVAX II is equipped with an 8-mm tape drive, a 6250/1600 bpi 9-track tape drive, and a Daphne data-acquisition system. Total disk storage for this cluster is about 7 GB.

Four of the VAXstations were upgraded from 8MB to 16MB of main memory in the first part of 1991 in order that large programs may be run on most of the machines in the cluster.

Computers within the Division have access to the following networks: Argonne DECnet, Bitnet, HEPnet, ESnet, and Internet.

The weak-interactions and medium-energy physics groups operate a VAXcluster of one VAXstation 3200, two VAXstation 3100, a MicroVAX II, and a VAX-750 which acts as the boot server. Total disk storage for this cluster is about 5 GB. The weak-interactions MicroVAX II is equipped with a 9-track tape drive and a Daphne data-acquisition system.

The Argonne members of BNL experiment E802 are using a Fermilab ACP computer system with 10 processors on the medium-energy physics VAX-750.

The ATLAS and Dynamitron VAX-750s continue to operate reliably. The Dynamitron VAX is routinely used for data acquisition and replay. The ATLAS VAX provides data acquisition for two simultaneous users at the ATLAS accelerator, as well as replay when CPU time and memory are available.

The Theory Group has installed an IBM RS/6000 workstation and an X-windows terminal.

The Atomic Physics Group and the Physics Division have each purchased and installed one Sun IPC workstation as a start in using Unix.

1. **Data-Acquisition Systems** (T. H. Moog, J. Sasso, and D. R. Cyborski)

DAPHNE, the data-acquisition system developed for ATLAS, is used routinely for experiments at ATLAS and the Dynamitron. Daphne was designed with hardware available in 1984 and has difficulty handling some of the more complex experiments that are planned. Because of this problem the Division decided to adopt the hardware for an acquisition system developed at the National Superconducting Cyclotron Laboratory of Michigan State University (MSU/NSCL) for the Argonne Positron Experiment (APEX). The MSU/NSCL system is unusual in that it transmits data to one or more machines over ethernet, allowing several users to analyze data from the same experiment independently. A number of changes have been made to DAPHNE at the request of the APEX group. Among these changes is the ability to accept data from the MSU/NSCL ethernet data stream and MSU/NSCL format tapes (in addition to the traditional DAPHNE hardware front-end and other supported tape formats). The APEX group plans to use DAPHNE software in combination with the MSU/NSCL front end for on-line data analysis.

We are investigating lower cost systems (with lower performance) for low-data-rate experiments and data-acquisition systems that will run under Unix.
Nuclear Target Development (J. P. Greene and G. E. Thomas)

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

In the past year, numerous targets were fabricated either as self-supporting foils or on various substrates. Targets produced included $^{27}$Al, $^{10}$B, $^{12}$C, $^{65}$Cu, $^{100}$Mo, $^{58,60}$Ni, $^{208}$Pb, $^{144,147}$Sm, $^{124}$Sn, $^{130}$Te, $^{22}$O$_3$ and $^{172}$Yb. Also developed were $^{58,64}$Ni "strip" targets for the FMA and $^{27}$Al/$^{197}$Au annular or "bulls-eye" targets for APEX beam testing. Carbon stripper foils of 2-µg/cm$^2$ for use in the Tandem are now being routinely produced. In addition, numerous carbon stripper foils were prepared for various experimental requirements ranging from 0.6 µg/cm$^2$ to 300 µg/cm$^2$. Established inventories of gold and carbon foils for a variety of the most common thicknesses has proved an efficient method for handling urgent requests.

The target development laboratory includes state-of-the-art equipment used for thin-film deposition. The available techniques consist of multiple resistive heating, focussed ion-beam sputtering, electron beam and electron bombardment evaporation. The evaporators are maintained under high vacuum and each vessel contains a quartz-crystal film-thickness monitor with deposition rate indicators. Also included are movable shutters, quartz-lamp substrate heaters and thermocouple temperature sensors. This allows for complete process monitoring during target deposition.

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

Because of increasing demand and coupled with the unavailability of commercial fabrication and suppliers, it has become necessary to roll foils at an accelerating pace. Using our small rolling mill, targets of $^{108}$Pd, $^{156,160}$Gd, $^{159}$Tb, $^{170}$Er, Yb and $^{198}$Pb were produced.

The IBM PC-XT laboratory computer is used extensively for a number of purposes. File archives maintained on this system include all targets produced, dating back to 1978. Computer listings can be generated for inventories of all stable isotopes and chemicals maintained by the target lab. An ADC board with software allows for acquisition and analysis of alpha-particle film-thickness measurements. A communications port attached to a PHYLIS line connects the computer to the Physics Division VAX, or by using KERMIT, to Argonne's central computing facilities. Electronic mail may be sent to "TARGETSANLPHY".

A target storage facility is in operation for maintaining, under high vacuum, those targets which can readily oxidize in air. This system utilizes a turbo pump and employs computer-controlled circuitry to prevent targets from exposure to atmosphere during power interruptions. A second, additional turbo-pumped chamber is now in routine use for target storage. This system uses electronically controlled valves for preserving the targets under high vacuum. There also exists a bank of vacuum desiccators connected to a mechanically-pumped manifold for use by individual experimenters.
Due to the need for various low-level radioactive sources and targets, a laboratory was assembled at a separate location, dedicated to the production of these foils. Targets of ThF$_4$ on carbon backings have been prepared in this lab for experiments at ATLAS, with UF$_4$ targets to be prepared similarly in the near future. The ability to produce these foils in-house is an important capability for the Physics Division.

A second, much smaller evaporator system was constructed for close proximity evaporations of higher activity materials, used not only as targets, but for radioactive source development as well. The size of this system allows for minimal contamination and is presently installed within a hood.

Radioactive source development is a new area which is beginning to see increasing effort. Using a small evaporator, $^{35}$S, $^{57}$Co, $^{109}$Cd sources have been prepared on thin carbon backings. Targets of $^{228}$Pa were also produced with this evaporator.

Within the APEX collaboration, at Florida State University, a similar effort has been mounted for production of uranium metal foils for APEX experiments. A new four-pocket Temescal electron beam gun has been procured and shipped to FSU. Target production will commence after installation is complete. Active participation in this effort by Argonne is continuing.
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. More than half of the running time is allocated to outside users. Until 1989 the accelerator system consisted of a 9-MV tandem injector coupled to a linac with 42 superconducting accelerating structures. This system provides projectiles with energies >5 MeV per nucleon for ions with mass $A < 100$. In 1989, the overall capabilities of the system began to be changed by a project to add a second injector, an ECR ion source followed by a 12-MV superconducting injector linac. For this positive-ion injector, now fully installed and operational, the goal was to extend the mass range up to uranium. A broad range of technology development that is closely linked to the needs of the ATLAS system is carried out under this program. In addition, the investigations of superconducting-linac technology include some topics that are of more general interest.

The layout of the ATLAS facility is shown in Fig. II-1. The original accelerator system in which a tandem injects ions into a superconducting linac has been in operation, in various stages of development, since 1978 and has provided users with more than 45,000 hours of beam on target.

During 1992 the research capabilities of ATLAS are being enhanced immensely by the completion of the new source of projectiles, the positive-ion injector (PII), shown on the left side of Fig. II-1. This system, which was completed and tested successfully off line in March 1992, is designed to accelerate ions from all parts of the periodic table, to increase beam currents substantially, and still to maintain the good quality of beams from the tandem.

Beam-acceleration tests of the complete PII-ATLAS system will be carried out during the Spring 1992 and, unless there is some unexpected difficulty, this system will be available for research by midyear. Thereafter, the tandem and PII will be used alternately as the source of projectiles for ATLAS, depending on user requirements.
Fig. II-1. Layout of the ATLAS facility. The new apparatus now coming into operation is the positive-ion injector (PII), on the left, and the experimental apparatus in Area IV, on the right.
A. OPERATION OF THE ACCELERATOR


A summary of past and projected operating statistics for ATLAS is given in the following table. The projected running time for FY 1993 is based on funding; attempts are being made to secure funding for additional operating hours.

### STATISTICS ON ATLAS USAGE

<table>
<thead>
<tr>
<th>Beam On Target for Research (hr)</th>
<th>FY 1991</th>
<th>FY1992</th>
<th>FY1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Physics</td>
<td>1744</td>
<td>2750</td>
<td>3200</td>
</tr>
<tr>
<td>Atomic Physics</td>
<td>209</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1953</td>
<td>3000</td>
<td>3500</td>
</tr>
</tbody>
</table>

| Number of Nuclear Experiments Receiving Beam | 34 | 35 | 37 |
| Number of Scientists Participating in Research | 121 | 125 | 140 |

### Institutions Represented

| Universities (U.S.A.) | 24 | 25 | 26 |
| DOE National Laboratories | 4 | 4 | 4 |
| Other | 13 | 12 | 12 |

### Usage of Beam Time (Z)

| In-House Staff | 42 | 45 | 43 |
| Universities (U.S.A.) | 53 | 50 | 52 |
| DOE National Laboratories | 2 | 2 | 2 |
| Other Institutions | 3 | 3 | 3 |

| Total | 100 | 100 | 100 |
The operation of ATLAS was interrupted for the first half of FY 1991 as a result of the finding of a DOE Tiger Team in October 1990. Operation was resumed in March 1991, under rules that are much more restrictive than had been applied in the past. The most significant change required that all beam areas must be unoccupied and locked while a beam is present or while RF resonators are powered. These requirements made it impractical to perform some approved experiments at ATLAS and have also made it difficult to carry out some maintenance activities around the accelerator. These stringent operating rules will remain in effect until a major upgrade of the radiation-safety system (scheduled for early summer 1992 and discussed in Sect. C) has been completed, reviewed, and approved.

The beam time provided by ATLAS was greatly reduced in FY 1991 because of the 6-month curtailment of operation and also because of a shortage of operating manpower which made it necessary to limit scheduled operation to 5 days per week. Nevertheless, the operational efficiency of the facility (defined as actual running time compared to scheduled time) was a very good 92%. The operational efficiency continues to remain high during FY 1992. The primary reasons for the improved performance are: the complete stability of the RF-distribution system (previously a problem), the use of calculated resonator-phase parameters (see Sec. B), more experienced operators, and a more systematic approach to operation and maintenance.

The second half of FY 1992 will be a very exciting period for the operation of ATLAS since, during this period, the PII-ATLAS system will be commissioned and then put into operation on a routine basis. In the initial use of PII for research, the emphasis will be on the acceleration of beams with mass greater than can be provided by the tandem injector, since the ATLAS users have expressed a great interest in such beams and a number of experiments requiring such beams have been approved by the ATLAS PAC. Beams that are of special interest are $^{48}$Ca, the molybdenum ions, $^{136}$Xe, $^{208}$Pb, and $^{238}$U. The beam time for research will be limited somewhat because of the developmental time required to bring the PII-ATLAS system into full operation and the time required to develop new beams. This kind of limitation should be largely eliminated by the end of 1992.

From the viewpoint of users, another major improvement scheduled to take place in mid 1992 is the completion and approval of the new radiation-safety system, which will allow users to have access to beam areas under many (but not all) conditions.

**B. RECENT IMPROVEMENTS AT ATLAS**

Improvements of the original tandem-linac ATLAS accelerator during the past year have focussed on improving operational reliability and efficiency. Significant benefits have already been realized from improved phase stability and associated tuning calculations and from the improved VCX-pulser design now in use. The control-system upgrade and refrigeration improvements will also improve our ability to deliver beam in a reliable manner.
B.1. **Linac Tune Calculations** (R. C. Pardo)

During the past year, software has been developed which allows tuned linac configurations of a specific charge-to-mass ratio (q/A) beam to be scaled for use with an ion species that has a similar q/A value. This has been made possible because of the greatly improved phase stability of the master oscillator distribution system. The new phase-distribution system has been previously reported.

This first application of calculated configurations has already significantly reduced the tuning time required for ATLAS and has improved operational flexibility. Further enhancements of these calculations are planned, but it will be necessary to improve a number of calibration parameters as part of this development effort.

B.2. **Upgrade of Linac Control System** (F. H. Munson, Jr. and M. Ferrarretto*)

An upgrade proposal for the fourteen-year-old ATLAS control system has been reviewed and approved by a panel of computer experts from within Argonne and the Physics Division. The new control system will make use of a commercial software product developed at Los Alamos National Laboratory (now commercialized) known as the VISTA System.

The core software and a subsystem of hardware needed for initial development is now in hand. Control of beam-line magnetic elements has been demonstrated off line, and development of the ATLAS-specific data base and control interface is in progress.

The implementation of the system will be phased into ATLAS operations over the next three years. The first attempt at use of the system in operation is approximately one year away. This project has benefited significantly from staff visiting Argonne from the University of Sao Paulo as part of the personnel-training program for their booster project.

This upgrade is designed to allow the new control system to be acquired and put into service piecemeal over a period of several years in order to minimize the impact on operation of the accelerator and on the capital-equipment budget. The planned approach will allow a large fraction of the high-level programs of the present control system to be carried over to the new system.

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*University of Sao Paulo, Brazil.*
B.3. **Upgrade of Fast Tuners (B. E. Clifft*)**

The RF-phase-controlling fast tuner of each resonator of the ATLAS linac consists of a voltage-controlled reactance (VCX) and a pulser to switch the PIN diodes on which the controlling action of the VCX is based. As reported previously, this system is being gradually upgraded by replacing the original fast tuners with units of improved design. The rate of this upgrading process has been determined by the availability of funds. During the past year, the replacement of all PIN-diode pulsers was completed, and the operational reliability of the system has been dramatically improved by this upgrade. In fact, no failure of a pulser unit was reported in the last six months. The lifetime of the PIN diodes has also been significantly improved by the new pulser design.

The next phase of the upgrade is to replace the VCX portion of the tuners with an improved design. See Sect. E.1.b. for additional information about the technology of the fast tuners.

B.4. **Area IV Status (W. Kutschera, R. C. Pardo)**

The switching magnet used to direct the ATLAS beam into each beam line of the new Area IV is a model magnet designed and built in about 1970 for the study of a proposed heavy-ion cyclotron. Since it was not designed for its present application, this magnet will be required to operate in a partially saturated mode for delivery of the highest-energy uranium beams to APEX. Concern that the beam quality would be degraded under these conditions has led to a study of beam transmission to APEX for beams of magnetic rigidity similar to high-energy uranium. These studies have shown that good beam quality can be maintained under these conditions. Beam size is excellent and no identifiable aberrations were detected.

B.5. **Helium-Refrigeration System (J. R. Specht and L. M. Bollinger)**

During the past year the helium-refrigeration and distribution system of ATLAS has been completed to the extent required for effective operation of PII. This work included completion of all parts of the helium distribution system (parts of which have been in place for several years) and the addition of another helium compressor. The new compressor is providing the additional refrigeration capacity that is essential for the PII linac and can also provide enough cooling to improve the performance of the booster linac.

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*Chemistry Division, ANL.*
B.6. Planned Improvements for the Near-Term Future

The completion of PII will soon result in an immense increase in the research capability of ATLAS. However, several upgrading tasks for the main ATLAS linac need to be carried out in order to realize the full potential of the accelerator system.

The fast-tuner upgrade described in B.3. and in E.1.b. needs to be completed. This upgrade is expected to improve operational reliability and to increase somewhat (10 to 20%) the maximum accelerating fields of resonators. To the extent that funding permits, this work will be carried out over the next two years as cryostats are opened for maintenance.

In view of the emphasis in the research program on experiments with beams of the heaviest ions, the velocity profile of the main ATLAS linac will be modified to be more suitable for ions such as \( ^{238}\text{U}^{40+} \). The present profile, which was established in 1982, was optimized for \( ^{58}\text{Ni}^{19+} \). The modification of the velocity profile will involve changing the RF frequencies of the last 10 resonators from 145.5 MHz to 97 MHz, thus making them more effective for the acceleration of ions with low charge-to-mass ratios.

When accelerating very heavy ions such as \( ^{238}\text{U} \) through the PII-ATLAS system, the ions must be stripped to a higher charge state at the output of PII. This stripping process produces a beam with many charge states, which makes it difficult to tune the remainder of the linac. For the present, this task will be accomplished by tuning the linac with a "guide beam" that has the same or approximately the same value of \( q/A \) as the beam of interest. We have demonstrated that this guide-beam technique is feasible and effective but it is also time consuming. Consequently, during 1992-93 a charge-state selector will be designed, built, and installed at the output of ATLAS so as to be able to tune directly the ion species of interest.

Funding for a second ECR ion source has been requested for FY 1994. This source is needed (a) to permit rapid changes in the nuclear species used for acceleration, (b) to allow maintenance of one source while the other is used for ion production, (c) to permit development of new ion species without interrupting normal accelerator operation, and (d) to improve source performance by taking advantage of the major advances in ECR source design that have taken place since our source was built in 1986-87. This last feature is especially important for high-energy beams of the heaviest ions and for beams produced from rare source materials such as \( ^{48}\text{Ca} \) in normal calcium.

C. SAFETY-RELATED ACTIVITIES AT ATLAS

The various activities in FY 1992 related to the safety program at ATLAS are summarized below. Most of this activity has been associated with the effort to bring PII on line and to develop a radiation-safety system that will enable experimenters to have access to beam areas. All of this activity is coming to a head during the first half of 1992.
The safety system for ATLAS continues to be formulated and implemented by collaboration between ATLAS management and those responsible for the safety system of the Physics Division as a whole, including especially the Division Director. During FY 1992, the relationship between this Physics-Division-based system and oversight by ANL Management and the DOE Argonne Area Office have been clarified, especially with regard to the responsibilities and mechanisms for safety reviews. Goals have been established for all aspects of safety at ATLAS, and the means for meeting these goals have been defined. The radiation-safety services provided by the ESH Division have been improved.

C.1. **Nuclear Model for Beam-Induced Radiation** (B. B. Back)

The analysis of all potential hazards at ATLAS has continued, with emphasis in FY 1992 on radiation, cryogenic, and SF\textsubscript{6} safety.

The part of the analysis process concerned with radiation safety has resulted in a comprehensive nuclear-model treatment that predicts the neutron and gamma radiation fields generated by heavy-ion beams stopped in various materials. The model is based on well-known characteristics of heavy-ion fusion reactions and the decay properties of compound nuclei formed in such reactions. The resulting flux of neutrons and gamma rays from the interaction region are converted to radiation fields on the basis of well-known energy-dependent conversion factors.

The results of the model calculations of quantities such as neutron and gamma multiplicities, energy spectra, angular distributions have been compared with experimental measurements wherever possible. Also, the predicted neutron-radiation fields have been compared with the sparse experimental data that are available. Based on this comparison, the model seems to provide a rather reliable prediction of the heavy-ion induced radiation fields at energies from about 10\% above the Coulomb barrier to about 20 MeV/nucleon.

The mathematical model resulting from the present work has been programmed into a FORTRAN code which runs on the VAX series computers from Digital Equipment Corporation.

C.2. **Documentation** (B. B. Back, L. M. Bollinger, and R. C. Pardo)

During FY 1992, four major safety documents of importance to ATLAS have been completed: (1) a Preliminary Safety Analysis Report for ATLAS (reviewed and approved), (2) a Cryogenic Safety Manual prepared by the Physics Division Cryogenic Safety Committee, (3) a Safety Analysis Report for ATLAS coupled to the positive-ion injector and operated with a new radiation-safety system (recently reviewed), and (4) a detailed technical description of the new ATLAS Radiation Interlock System. Operation Readiness Review reports for the new safety system still need to be prepared. All of these documents have been or are being reviewed by objective technically-competent committees.

In addition to these major documents, numerous new or modified operating procedures were written and safety-analysis documents concerning many aspects of the accelerator system and all experimental equipment have been prepared and reviewed.
C.3. Engineered Safety Equipment

During FY 1992, the effort devoted to engineered safety equipment at ATLAS has focussed on those items that must be functional before ATLAS can be operated under the new Safety Analysis Report. The nature of this equipment is summarized below. This equipment provides several independent and redundant means for radiation protection at ATLAS.


A new ATLAS Radiation Interlock System (ARIS) has been designed and is being implemented. This system will provide radiation protection for both planned (usually low-level) radiation levels and for worst-case levels that could be generated accidentally. An important feature of ARIS is that it integrates the radiation-dose rate in a beam area while it is occupied, and automatically inhibits the beam if the integrated dose exceeds a prescribed value during any eight-hour period. This feature enables experimenters to enter beam areas safely in order to adjust equipment parameters, an essential capability for many experiments at ATLAS.

The new ATLAS Radiation Interlock System is based on an industrial processor SY/MAX that controls Faraday cups, warning lights, bells, etc., based on information obtained from various sense switches which show the state of access gates, beam line valves, etc. This basic system is being augmented with a second computer (an IBM/PC) which gathers information about the radiation levels in the various beam areas, analyzes this information, and communicates the results back to the SY/MAX. In addition, each beam area will be equipped with a status display that provides up-to-date information about the access state of the area and the measured radiation levels in the area.

ARIS has been designed and programmed entirely by Physics Division personnel.

A comprehensive document describing the design criteria and technical implementation of the ARIS system has been written and will undergo a technical review by an outside committee.

C.3.b. Beam-Current Interlock System (J. Bogaty, B. E. Clifft,* L. M. Bollinger, and R. C. Pardo)

The key element of this interlock system is a pair of capacitive beam-current detectors that continuously and non-destructively monitor the beam current injected into the main ATLAS linac and cause the beam to be stopped in a fraction of a second if the measured current exceeds a prescribed limiting value. Additional information concerning this redundant fail-safe device is given in Sec. E.1.e.

The beam-current interlock system, which is entirely independent of the Radiation Interlock System, will be put into service during March 1992. Its main function is to provide protection from the intense radiation that could result from unplanned large increases in beam current from the ECR ion source.

*Chemistry Division, ANL.
C.3.c. **Beam-Current Attenuator** (R. Vondrasek, R. C. Pardo, and L. M. Bollinger)

An interlocked beam-current attenuator is being installed at the output of the ECR source. The function of this device is to enable the beam current to be attenuated (when needed) in such a way that the current cannot accidentally be increased by a large factor. This protective feature is needed because the ECR source can provide much greater currents of light ions than are needed for most experiments.

C.3.d. **Shielding** (J. M. Specht and L. M. Bollinger)

The shielding around beam areas at ATLAS is being strengthened at a few places. This improvement is aimed at ensuring that, during normal operation, all work areas adjacent to a beam area can be safely occupied.

C.3.e. **Oxygen-Deficiency Safety System** (R. C. Pardo and S. L. Craig)

Although the probability of asphyxiation at ATLAS from an accidental release of helium or SF$_6$ is very small, the risk from this hazard is being reduced further by the installation of an oxygen-deficiency detection and interlock system. Oxygen sensors will be installed in a number of locations to detect any lowering of the oxygen content, sound alarms when a hazardous condition occurs, and automatically open doors or fans in order to remove the hazardous gas. The installation of this safety system will be phased over the next year. Sensor installation is now underway, area alarms will be installed later in FY 1992, and the system will be completed in FY 1993.
D. ASSISTANCE TO OUTSIDE USERS OF ATLAS  
(B. G. Glagola)

The continuing strong interest in ATLAS (outside users were involved in 84% of all experiments performed in 1991) makes it clear that the user-assistance program fills an essential function.

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

The Program Advisory Committee (PAC) for ATLAS (consisting of five members from other institutions and two from Argonne) continues to meet regularly during the year. PAC meetings were held on June 15, 1991 and December 7, 1991 to recommend experiments for running time at ATLAS. The present PAC members are Daniel Dietrich (Lawrence Livermore Laboratory), Teng Lek Khoo (ANL), Christopher Lister (Yale University), Robert McGrath (SUNY at Stony Brook), Karl Ernst Rehm (ANL), Wolf-Udo Schroeder (University of Rochester), and David Ward (Chalk River Nuclear Laboratories). The PAC reviewed 27 proposals for 162 days and 24 proposals for 134 days of running time at each meeting, respectively. The demand for running time at ATLAS continues to be more than the available accelerator time.

The ATLAS User Executive Committee organized a User Group meeting during the October 1991 Division of Nuclear Physics APS meeting held in East Lansing, Michigan. The meeting was attended by approximately 40 scientists. The main topics of discussion were the FMA project, the positive-ion-injector ATLAS upgrade and APEX, the positron experiment at ATLAS. The ATLAS Executive Committee consists of Stephen Sanders (University of Kansas), as Chairperson, Jolie Cizewski (Rutgers University), Patrick Daly (Purdue University), and Christopher Lister (Yale University).

Outside users are involved heavily in the Fragment Mass Analyzer project. A number of universities are constructing experimental equipment for use on the FMA. For more details see section I.E.a., on the Fragment Mass Analyzer.
The prospect of uranium beams in 1991 has brought about an ANL-FSU-MSU-Princeton-Queen's-Rochester-Washington-Yale collaboration to design and construct an experiment to investigate and resolve the question of "anomalous positron peaks" that have been seen at GSI. The outside members of the APEX collaboration are: S. Austin, D. Bazin, E. Kashy, D. Mikolas, M. Robertson, J. Winfield, J. Yurkon, Michigan State University; J. Greenberg, C. Lister, P. Chowdhury, K. Chan, A. Chisti, N. Koloskamis, Yale University; F. Calaprice, Princeton University; A. Hallin, Queen's University; J. Fox, D. Roa, Florida State University; F.L.H. Wolfs, S. Gazes, A. Perera, University of Rochester; T. Trainor, University of Washington; and M. Maier, Lawrence Berkeley Laboratory. The apparatus is currently being installed. For more details see section I.E.b., on the APEX project.

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

D.a. Experiments Involving Outside Users

All experiments in which outside users participated during calendar year 1991 are listed below. The spokesperson for each experiment is given in square brackets after the title. The names in parentheses are Argonne collaborators.

1. Sub-Barrier Anomalies in Fission Angular Distributions [Fernandez]
   Y. Nagame, JAERI, Japan; (B. Back, P. Fernandez, T. Happ, A. Wuosmaa, D. Henderson, J. Gehring, B. Glagola)

2. Search for Multiple Superdeformed Bands in $^{189}$Hg [Janssens]
   I. Bearden, Ph. Benet, Purdue University; A. Baxter, Australian National University; D. Ye, W. Reviol, U. Garg, University of Notre Dame; (R. Janssens, P. Fernandez, I. Ahmad, T. Khoo, M. Carpenter, T. Lauritsen)

3. Superdeformation in $^{196}$Pb [Janssens]
   I. Bearden, Ph. Benet, Z. Grabowski, R. Mayer, B. Fornal, Purdue University; D. Ye, W. Reviol, University of Notre Dame; (R. Janssens, I. Ahmad, T. Khoo, M. Carpenter, T. Lauritsen, P. Fernandez)

4. Competition Between Decay in the Superdeformed Well and Fission [Khoo]
   Ph. Benet, I. Bearden, Purdue University, A. Baxter, Australian National University; D. Ye, University of Notre Dame; (T. Khoo, M. Carpenter, B. Back, R. Janssens, I. Ahmad, M. Freer, A. Wuosmaa, T. Lauritsen)

5. Quasicontinuum Gamma Rays from the Decay of the Superdeformed Band in $^{192}$Hg [Khoo]
   A. Baxter, Australian National University; D. Ye, University of Notre Dame; Ph. Benet, I. Bearden, Purdue University; (T. Lauritsen, T. Khoo, I. Ahmad, M. Freer, M. Carpenter, R. Janssens, A. Wuosmaa)
(6) Test of CsI Detectors [DeYoung]
P. DeYoung, R. Sedlar, D. Peterson, Hope College

(7) Commissioning Tests of the FMA [Davids]
P. Sugathan, NSC New Delhi; K. Bindra, A. Ramayya, Vanderbilt University; Y. Nagame, JAERI, Japan; J. Kolata, W. Chung, D. Nisius, University of Notre Dame; S. Freeman, Yale University; W. Walters, University of Maryland; R. Kozub, Tennessee Technological University; T. Crawford, Iowa State University; (C. Davids, B. Back, D. Henderson, T. Lauritsen, W. Kutschera)

(8) Beam Line Tests of a Large-Area Bragg-Curve Spectrometer [Sanders]
S. Sanders, F. Prosser, K. Farrar, A. Hasan, University of Kansas; (D. Henderson)

(9) The Structure of Light Polonium Nuclei [Cizewski]
J. Cizewski, L. Farris, R. Henry, C. Lee, Rutgers University; Ph. Benet, I. Bearden, Purdue University; D. Ye, University of Notre Dame; (R. Janssens, T. Khoo, M. Carpenter, I. Ahmad, P. Fernandez)

(10) Shape Coexistence in $^{192}$Pb [Garg]
A. Plompen, J. Van Schagen, G. Van't Hof, N. Kalanter-Nayestanaki, M Harakeh, Vrije Universiteit; U. Garg, W. Reviol, D. Ye, University of Notre Dame; I. Bearden, Purdue University; (R. Janssens, T. Khoo, M. Carpenter, I. Ahmad, T. Lauritsen)

(11) Search for Resonance Behavior in $^{12}$C+$^{12}$C+$^{12}$C($0^+2$)+$^{12}$C($0^+2$) Inelastic Scattering [Wuosmaa]
I. Bearden, Purdue University; (A. Wuosmaa, B. Back, R. Betts, M. Freer, D. Henderson, T. Happ, B. Glagola)

(12) Search for "Necked" Superdeformation in the $A = 90$ Region [Garg]
U. Garg, S. Naguleswaran, A. Aprahamian, W. Reviol, J. Walpe, D. Ye, University of Notre Dame; I. Bearden, Purdue University; (I. Ahmad, M. Carpenter, R. Janssens, T. Khoo, T. Lauritsen)

(13) Test of a 4-f Detector Element [Viola]

(14) Energy of the $2(^3S_1) - 2(^3P_0)$ Transition in Helium-Like Ni$^{26+}$ [Livingston]
A. Livingston, University of Notre Dame; (R. Dunford, C. Liu, G. Berry)

(15) APEX Beam Tests [Betts]
T. Trainor, University of Washington; S. Austin, E. Kashy, J. Winfield, J. Yurkon, D. Bazin, M. Robertson, Michigan State University; D. Mikolas, Cornell University; A. Hallin, Queens University; F. L. Wolfs, S. Gazes, A. Perera, University of Rochester; K. Lister, N. Kaloskamis, K. Chan, Yale University; F. Calaprice, Princeton University (R. Betts, W. Kutschera, J. Schiffer, M. Freer, T. Happ, A. Wuosmaa, R. Dunford)
(16) Octupole Deformations in SD Nuclei: the Case of $^{196,195}$Pb [Janssens]
I. Bearden, B. Fornal, Purdue University; D. Ye, W. Reviol, A. Aprahamian, University of Notre Dame; (R. Janssens, M. Carpenter, I. Ahmad, T. Khoo, T. Lauritsen, Y. Liang)

(17) Dynamical Screening of Channeled Ions [Kanter]
D. Zajfman, Weizmann Institute; J. Tanis, R. Haar, S. Ferguson, Western Michigan University; D. Schneider, M. Clark, Lawrence Livermore National Laboratory; W. Graham, Queens University; (E. Kanter, E. Rehm)

(18) Spectroscopy of Sn Isomers from Deep-Inelastic Reactions [Daly]
P. Daly, B. Fornal, R. Mayer, Z. Grabowski, I. Bearden, Purdue University; (R. Janssens, I. Ahmad, T. Khoo, T. Lauritsen, Y. Liang)

(19) Test of a PGAC Detector [Rehm]
G. Hardie, R. Bent, Western Michigan University; Z. Yu, Northwestern University; C. Sun, Indiana University; (E. Rehm, J. Gehring, Y. Liang)

(20) Test Run for High-Temperature Phenomena in Proton-Rich Nuclei [McGrath]
A. Caraley, B. Fineman, SUNY Stony Brook; (B. Glagola, A. Wuosmaa)

(21) Superdeformation and Octupole Shapes [Janssens]
B. Fornal, Purdue University; W. Reviol, U. Garg, University of Notre Dame; F. Soramel, University of Padova; (R. Janssens, T. Khoo, I. Ahmad, M. Carpenter, Y. Liang, T. Lauritsen)

(22) Entrance-Channel Dependence in the Population of the SD Band in $^{192}$Hg [Khoo]
W. Reviol, U. Garg, University of Notre Dame; B. Fornal, R. Mayer, I. Bearden, Purdue University; F. Soramel, University of Padova; (T. Khoo, I. Ahmad, R. Janssens, M. Carpenter, T. Lauritsen, Y. Liang)

(23) Two-Photon Decay of He-Like Br$^{33+}$ [Dunford]
A. Livingston, University of Notre Dame; L. Curtis, University of Toledo; (R. Dunford, S. Cheng, E. Kanter, G. Berry, C. Kurtz, J. Sulieman)

(24) Production of 2.2-Day $^{203}$Pb [Kutschera]
M. Paul, Hebrew University; B. Schneck, Technical University Munich; (W. Kutschera, I. Ahmad)

(25) Angular Distribution Measurement for $^{12}$C+$^{12}$C+$^{12}$C(0$^+_2$)+$^{12}$C(0$^+_2$) Inelastic Scattering [Wuosmaa]
I. Bearden, Purdue University; (A. Wuosmaa, B. Back, R. Betts, M. Freer, J. Gehring, T. Happ, D. Henderson, B. Glagola)
(26) Alpha Decay Rates of $^{180,182}$Pb [Toth]
K. Toth, Oak Ridge National Laboratory; J. Robertson, University of
Kentucky; D. Moltz, Lawrence Berkeley Laboratory; W. Walters,
University of Maryland; W. Chung, University of Notre Dame;
K. Bindra, Vanderbilt University; C. Bingham, University of
Tennessee; (C. Davids, B. Back, D. Henderson)

(27) Development of a $^{17}$F Beam for Astrophysical Reaction Rate Studies [Wang]
T. Wang, Lawrence Livermore National Laboratory; M. Paul, Hebrew
University; (W. Kutschera, R. Pardo, E. Rehm, J. Schiffer,
B. Glagola)

(28) Search for Superdeformation in $^{191}$Tl [Pilotte]
S. Pilotte, University of Ottawa; L. Riedinger, C. H. Yu, J. Lewis,
University of Tennessee; I. Bearden, Purdue University; (R. Janssens,
I. Ahmad, M. Carpenter, T. Lauritsen, Y. Liang, T. Khoo)

(29) High-Resolution Q-Value Measurement of $^{48}$Cr Fission Fragments [Sanders]
S. Sanders, F. Prosser, K. Farrar, A. Hasan, University of Kansas;
A. Szanto de Toledo, University of Sao Paulo; (B. Back, R. Betts,
M. Freer, A. Wuosmaa, R. Janssens)

D.b. Outside Users of ATLAS and of ATLAS Technology During the Period
January 1 - December 31, 1991

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

(1) University of Kansas
   F. Prosser
   S. Sanders
   * K. Farrar
   * A. Hasan

(2) University of Notre Dame
   U. Garg
   * D. Ye
   J. Kolata
   * L. Chung
   * J. Walpe
   W. Reviol
   A. Livingston
   * S. Naguleswaran
   A. Aprahamian
   * C. Kuhla
   * M. Herr
   * S. Dixit
   * R. Tighe
   * F. Serpa
   * M. Nielsen
(3) Purdue University
   P. Daly
   Z. Grabowski
   P. Benet
   * I. Bearden
   * R. Mayer
   * D. Nisius
   B. Fornal

(4) Idaho National Engineering Lab
   M. Drigert

(5) Vanderbilt University
   A. Ramayya
   * K. Bindra

(6) Australian National University
   A. Baxter

(7) SUNY Stony Brook
   * A. Caraley
   * E. Fineman

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

(9) JAERI, Japan
   Y. Nagame

(10) University of Rochester
    P. Wolfs
    S. Gazes
    * A. Perera

(11) University of Iowa
    I. Crawford

(12) Weizmann Institute
    D. Zajfman

(13) University of Toledo
    L. Curtis

(14) Hope College
    P. DeYoung
    * R. Sedlar
    * D. Peterson
(15) NSC, New Dehli
   * P. Sugathan

(16) Vrije Universiteit, Amsterdam
   * A. Plompen
   * J. Van Schagen
   * G. Van't Hof
   M. Harakeh
   N. Kalanter-Nayestanaki

(17) University of Padova
    F. Soramel

(18) University of Maryland
    W. Walters

(19) Yale University
    K. Lister
    P. Chowdhury
    J. Greenberg
    * K. Hahn
    * R. Curley
    A. Chishti
    * N. Kaloskamis
    * K. Chan
    * R. Dixon
    S. Freeman

(20) Rutgers University
    J. Cizewski
    C. Lee
    * L. Farris
    * R. Henry
    * L. Bernstein

(21) University of Tennessee
    L. Riedinger
    C. Bingham
    * J. Lewis
    C. H. Yu
    * H. Jin

(22) Hebrew University
    M. Paul

(23) Kansas State University
    T. Gray
    K. Karnes
    V. Needham
(24) Florida State University
   J. Fox
   E. Myers
   * E. Roa

(25) University of Sao Paulo
   J. Ordonez
   O. Sala
   M. Ferraretto
   N. Added
   A. Szanto de Toledo

(26) Michigan State University
   S. Austin
   E. Kashy
   J. Winfield
   J. Yurkorn
   D. Bazin
   M. Robertson

(27) Princeton University
   F. Calaprice

(28) Univ. Nac. Auto. de Mexico
   J. Vega

(29) Oak Ridge National Laboratory
   K. Toth

(30) Tennessee Technological University
   R. Kozub

(31) Indiana University
   V. Viola
   K. Kwiatkowski
   J. Brzychczyk
   * D. Bracken
   * E. Renshaw
   * K. Morley
   C. Sun

(32) Lawrence Berkeley Laboratory
   M. Maier
   D. Moltz

(33) Western Michigan University
   J. Tanis
   R. Haar
   S. Ferguson
   G. Hardie
   Z. Yu
   F. Chen
   R. Bent
Several groups from the University of Notre Dame are playing an important role in developing the research program at ATLAS. One of their main interests is the study, in collaboration with ANL staff members, of the behavior of nuclei at high spin in the transitional region near $^{208}$Pb (i.e. the Hg-Pt-Os nuclei), and Sn (i.e. the Ru-Pd nuclei) with emphasis on shape coexistence and configuration mixing. This group has also participated in most of the experiments performed with the recently completed BGO gamma-ray facility. A graduate student, Mr. D. Ye, was based at Argonne until the completion of his thesis work under the direct supervision of R. V. F. Janssens. Another project concerns the study of quasielastic heavy-ion reactions using $^{208}$Pb targets.
A major activity of this past year was the continued maintenance and development of the gamma-ray facility consisting of a BGO sum-multiplicity array of 50 elements combined with 12 Compton-suppressed germanium detectors. In this project, the Notre Dame group is responsible for the array. Additionally, part of the Notre Dame group has built and tested a Bragg-curve detector for use in the focal plane of the fragment mass analyzer.

(ii) Atomic Physics (A. E. Livingston)

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 current goal is to measure the $^{23}\text{S}_1 - ^{23}\text{P}_0$ transition energies in helium-like Ni$^{26+}$ and Ar$^{16+}$. Precise measurements of $2s-2p$ transition energies in simple (few-electron) atomic systems provide stringent tests of several classes of current atomic-structure calculations. Another program being conducted in collaboration with Argonne and E. Trabert of Bochum University in Germany aims at measuring lifetimes of intercombination transitions in Mg-like, Al-like and Si-like krypton. The group is also participating in measurements of the forbidden lifetimes in helium-like ions. 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. In the past year a measurement was made of the lifetime of the $^2\text{S}_0$ level in helium-like bromine.

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

The Purdue University group, including several thesis students, is working on high-spin nuclear states at ATLAS. They use in-beam gamma-ray techniques directed at several aspects of nuclear structure at high spin, testing the validity of the $Z = 64$ sub-shell closure through spectroscopic studies of $N = 82$ nuclei close to the proton drip line. They have extended these studies in the last year by making use of the Compton-suppressed germanium detectors of the BGO facility. In particular, a study of $^{143}\text{Eu}$ and $^{144}\text{Gd}$ is underway. The group has also built a superconducting solenoid lens that is used as a conversion-electron spectrometer. The group has provided assistance to other users of this device.

A member of the group is currently based at Argonne in order to facilitate interactions with the local group and to speed up the analysis effort. Furthermore, I. C. Bearden is a PhD student, resident at ANL, performing his thesis work under the supervision of R. V. F. Janssens. The group has also initiated a new direction in research where gamma-ray techniques are used to derive information on the cross section for deep-inelastic and transfer channels in the vicinity of the Coulomb barrier. The group has used these types of reactions to perform spectroscopy studies on neutron-rich nuclei with $Z \approx 50$ that cannot be studied by other means.
c.3. University of Kansas
(F. W. Prosser, S. Sanders, K. Farrer, and A. Hasad)

The group continued to study the process where relatively light compound nuclei (Acn < 60) decay through a binary fission mode. The focus of this work is to develop experimental signatures of the structure of the compound system at the point of breakup. These studies, which involve particle-particle and particle-gamma coincidence measurements of a relatively low cross-section process, have led to the group developing a large acceptance (12" x 12" window) Bragg-curve detector. This detector can either be mounted on one of the ports of the 36" scattering chamber or on one of the 6 ports of the large, particle-scattering chamber developed for the Argonne-Notre Dame gamma-ray facility. Beam tests of this detector were successfully completed during the year. At the end of the year this group had a successful run, in collaboration with researchers from Sao Paulo, Brazil, and Argonne, in which they studied the fission of 48Cr as populated in the 24Mg + 24Mg reaction. A high-resolution Q-value spectrum was obtained for this process using a kinematic coincidence technique. The Kansas Bragg-curve detector supplied complete particle identification. The group plans to continue these studies of the nuclear structure related to the fission of light systems with another particle-gamma coincidence measurement using the 40Ca + 16O reaction. They are also in the process of developing a hybrid, position-sensitive, multi-wire proportional counter (MWPC)--Bragg-curve detector which will allow them to avoid using a separate MWPC in front of the Bragg. By avoiding the extra pressure windows they can increase the dynamic range of their counter while achieving a simpler experimental configuration.

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

A program is in progress to carry out accurate spectroscopic measurements of X-ray transitions in hydrogen-like and helium-like calcium to provide important tests of QED and relativistic quantum mechanics. In order to produce clean spectral lines in the experiment, a gas target is being used to obtain the excited helium-like or hydrogen-like ions. To get reasonable cross sections for electron pickup, the technique of accel/decel is employed, whereby beams of one-electron ions are obtained by stripping after the booster and then slowing down in the ATLAS section of the Linac. Data analysis is in progress for a measurement of the 2p-2s transition energies in He-like calcium. A beam of Ca19+ was accelerated to 205 MeV and then decelerated to 105 MeV and delivered to the atomic physics beamline. A crystal spectrometer and a gas target installed on the beamline were used to make precision X-ray measurements. Plans are in progress for making improvements to the beam diagnostics, gas cell and X-ray spectrometer in preparation for another run in the coming year which would utilize the higher beam currents available from the positive-ion injector.
c.5. Idaho National Engineering Laboratory (M. W. Drigert)

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

D.d. ATLAS-Technology Transfer

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

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

Argonne has fabricated the niobium resonators and some auxiliary devices required for the superconducting-linac energy booster being built at Florida State University. Under this arrangement, personnel from FSU have come to ANL to assemble and test the resonators. The main resonator fabrication work for FSU was completed during 1986, but we continue to interact with personnel concerning ongoing refinements in the technology and to assist occasionally in the solutions of technical problems.

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

Argonne has fabricated the niobium resonators and some other linac components required for the superconducting decelerating linac being built at Kansas State University. Several staff members from KSU spent a substantial period of time at ANL during FY 1985 in order to learn the technology, and they have continued to return occasionally since then to assemble and test the resonators. There is a continuing active interchange of technical information between ANL and KSU.
d.3. University of Sao Paulo (N. Added, M. Ferrarretto)

Argonne has undertaken to assist the University of Sao Paulo (USP) in the construction of a small superconducting heavy-ion linac to serve as an energy booster for projectiles from their 8-MV tandem. This booster will be similar in many respects to the ANL booster linac built in the late 1970s. The ANL contribution to this project is (1) to build (at USP expense) 14 split-ring niobium resonators, (2) to provide technical information, and (3) to train USP staff members in several phases of superconducting-linac technology.

The construction of resonators for USP began in late 1991. Six of these units will be completed in early 1992 and six more will be completed in late 1992. To date, four Brazilian engineers have worked at Argonne in order to gain experience in cryogenics, superconducting-resonator technology, RF technology, and computer control of a superconducting linac.

d.4. Nuclear Science Centre, Delhi (P. N. Potukuchi, A. Roy)

Argonne is collaborating with the Nuclear Science Centre in a joint project aimed at the development of a new type of superconducting accelerating structure for low-velocity ions. The intent of the planned project is to design, fabricate, and test a prototype unit, and to develop a conceptual design for a heavy-ion linac based on this prototype.

Two staff members from the Nuclear Science Centre are working at Argonne in order to gain familiarity with the existing superconducting-linac technology and to contribute to the planned developmental effort.

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

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

Efforts are directed toward the identification of institutions with relatively strong physics programs and with faculty interested in stimulating their students to pursue research activities and summer programs. During visits to colleges, lectures are presented and are followed by discussion of activities in physics, at Argonne and other national laboratories, and the possibilities for graduate study, employment, etc.

Additional activities included attending meetings of the Society for the Advancement of Chicanos and Native Americans in Science and of the Society of Black Physics Students.
As a result of these efforts, 35 applications were received for the summer program in 1991. A total of 28 offers were made for the Summer Research Participation program in conjunction with Argonne's Department of Educational Programs. The program was resumed early in FY 1992 with return visits to some of the institutions that had been visited previously. Additional institutions will be visited during this year and several meetings of minority groups will be attended. These ongoing interactions appear to be generating institutional relationships that will enrich the physics programs in minority institutions and substantially enhance minority involvement not only in nuclear physics, but in other branches of physics and science.

E. SUPERCONDUCTING LINAC DEVELOPMENT


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

In view of the pioneering nature of the work at ATLAS, there are continuing needs to upgrade the existing technology and continuing opportunities to develop new approaches. This developmental effort is essential for the research-effectiveness of the ATLAS facility.

The developmental activities at ATLAS include (1) refinement of ATLAS and its positive-ion injector, (2) investigations of the basic technology of RF superconductivity, and (3) the development of new kinds of accelerating structures.

E.1. Status of the Positive-Ion Injector

The new positive-ion injector (PII) consists of an electron-cyclotron-resonance (ECR) ion source on a voltage platform followed by a new class of superconducting injector linac. Multiply-charged ions from the source are transported to the injector linac by way of a beam-preparation system that includes two stages of magnetic analysis and two stages of bunching. The injector linac consists of 18 four-gap accelerating structures housed in three cryostats. The nominal accelerating voltage for this array is 12 MV. The layout of the injector system is shown in Fig. II-2.

*Chemistry Division, ANL.
All sub-systems of the system have been completed and tested. A 3-MV version of the linac was first operated for beam acceleration in March 1989 and, following this successful test, was then used occasionally until December 1989 to accelerate ions into the ATLAS linac. A 7-MV version of the linac was then completed and was first operated in a beam-acceleration test in March 1990. This system was used occasionally until July 1990 to inject test beams into ATLAS for acceleration to the experimental area. These tests demonstrated that the design goals for the positive-ion injector project would be met and that the longitudinal emittance of the beam from the new injector sets a new standard of excellence.

The installation of PII was completed in early March 1992, and by the end of March beams of $^{30}\text{Si}^{+7}$, $^{40}\text{Ar}^{11+}$, $^{132}\text{Xe}^{13+}$, and $^{208}\text{Pb}^{24+}$ had been accelerated successfully by it. The system operated as expected in all respects. The planned beam-output energy (see Fig. II-3) was achieved, beam transmission was $\approx 100\%$, and both transverse and longitudinal emittance were good.

In view of the excellent performance of PII alone, it is expected that beams from PII can be accelerated through the main ATLAS linac with ease. This next and final step will be undertaken during the period April-June 1992.

Additional information about the status of individual subsystems of PII is given below.
Fig. II-3. Output beam energy of the positive-ion injector. Here $\phi_0$ is the RF phase-offset angle (typically 150°) and $\rho$ is the ratio of the actual accelerating fields to the design fields for the superconducting resonators. The indicated operating point for $^{238}$U$^{24+}$ is for $\rho = 1$, whereas experience indicates that $\rho$ can be at least 1.15.

E.I. a. ECR Source and Voltage Platform (R. C. Pardo and P. J. Billquist)

Utility power for the ECR source and other devices on the voltage platform is provided by 350-kV isolation transformers. The units acquired originally for this purpose proved to be very unreliable and were replaced in mid-1991 with new transformers provided by a different manufacturer. All experience to date indicates that the new units operate reliably over long periods of time and will satisfy all requirements.

Since October 1990, the primary effort on the ECR source itself has been devoted to upgrading its safety system. This work was completed in May 1991.
The present work on the ECR source is being directed toward the development of beams of very heavy nuclear species. Such beams are needed for beam-acceleration tests of the whole system and for some of the first experiments that will use PII as the source of projectiles. This emphasis on the heaviest ions will continue throughout FY 1992.

E.1.b. **Injector Linac**

(a) **Resonators and Cryostats** (K. W. Shepard, P. Markovich, and G. P. Zinkann)

The final configuration of the injector linac is shown in Fig. II-4. All of the 18 resonators and 3 cryostats of the injector linac have been fabricated, tested successfully off line, and installed on line. During the past few months, all three cryostats loaded with their resonators have been cooled down and tested on line, and several kinds of small problems have been detected and corrected. This phase of the commissioning process is now complete.

**CONFIGURATION OF PII LINAC**

![Configuration of the PII linac. All resonators are 4-gap interdigital structures. Each superconducting solenoid forms a waist in the following resonator(s). The internal diagnostic detector is a fast Faraday cup with a time resolution of 200 ps, the first use of such a refined device in the cold region of a superconducting linac.](image)

Fig. II-4. Configuration of the PII linac. All resonators are 4-gap interdigital structures. Each superconducting solenoid forms a waist in the following resonator(s). The internal diagnostic detector is a fast Faraday cup with a time resolution of 200 ps, the first use of such a refined device in the cold region of a superconducting linac.
(b) Phase Control (K. W. Shepard, B. E. Clifft,* N. Added,† and G. P. Zinkann)

A PIN-diode based, 77K voltage-controlled reactance (VCX) is used to control the phase of the superconducting resonators in PII. The operational demands on this device for the PII resonators are considerably more severe than for the other ATLAS resonators.

A prototype of the VCX for PII was tested successfully off line but was found to be inadequate in long-term online use. Consequently, the system has been numerically modeled, the results of which show how to achieve better matching of the RF current and voltage to the characteristics of the PIN diodes operated at 77K. The dominant failure mode was found to be caused by transients exceeding the power-current-voltage capabilities of the diodes. By using the numerical modeling to optimize the design of the VCX the reactive power of the device has been increased from 20 to 30 kVA, thus enabling a proportional increase in the phase-tuning power of the device. This improved tuning power is 6 times greater than is achievable with the units still used on most of the ATLAS resonators.

(c) Liquid-Helium System (J. M. Specht and L. M. Bollinger)

An additional helium compressor has been procured and installed in order to increase the refrigeration capacity of the refrigerator used to cool PII. The new compressor has been tested successfully and is now being used routinely.

E.l.c. Beam Preparation System (R. C. Pardo, P. J. Billquist, and R. Vondrasek)

The beam preparation system of PII transports the beam from the ECR source to the injector linac and prepares the beam for injection into the linac with optimum characteristics in both transverse and longitudinal phase space.

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*Chemistry Division, ANL.
†University of Sao Paulo, Brazil.

Several improvements made during the past year or now in progress are expected to improve performance of an already refined system. These improvements are (a) modification of the transverse linac-injection optics, (b) enlargement of the transverse acceptance of the first-stage buncher, and (c) the installation of a beam-current-limiting system that is part of the safety system of ATLAS but will also provide operational flexibility.

E.l.d. Beam Diagnostics (J. Bogaty)

Last year we reported the development of a fast Faraday cup that sets a new performance standard for the time resolution of beam-pickup probes. The unit designed for use with beams from the ECR source are now used routinely to study these beams and to tune the beam-buncher on the voltage platform.

During the past year, a fast Faraday cup with the greater sensitivity and faster rise time required for use at the output of ATLAS has been developed. This device is expected to shorten the time required to tune the bunched beams delivered to users, but it is not feasible in FY 1992 to implement this improvement because of a shortage of funds.
E.1.e. Beam-Current Monitor (J. Bogaty, B. E. Clifft, L. M. Bollinger, and R. C. Pardo)

A beam-current monitor and interlock system has been developed as part of the engineered safety system at ATLAS. This device, based on a pair of cylindrical RF pickup probes, is non-destructive, has almost linear response over a current range of three orders of magnitude, is redundant in several independent ways, is self-testing and fail safe, and can generate a signal to stop the beam in \(< 2\) ms. The main function of this beam-current interlock system is to provide protection from radiation that could be produced by the accidental acceleration of intense light-ion beams from the ECR source.

E.2. Basic Technology of RF Superconductivity

There are two parts to this work. One is a continuing investigation of many aspects of the basic technology of RF superconductivity. The second is a part-time effort by a member of the Physics Division, working in collaboration with others, to develop new kinds of low-\(\beta\) superconducting accelerating structures.

E.2.a. Basic Technology Studies (K. W. Shepard)

The initial focus of this program is to study the limiting factors for electric fields in superconducting accelerating structures. Of particular interest are the phenomena causing electron multipacting and field emission, which limit the performance of both low-velocity and high-velocity structures, although in different ways.

A resonator-test facility dedicated to the study of basic RF superconducting technology is nearing completion. The facility consists of a test cryostat that can be cooled with liquid helium from a distribution line linked to the ATLAS helium-refrigeration system, thus enabling long-term tests to be carried out. Interface hardware and software for a PC-based computer control and data-acquisition system have been completed for RF and vacuum systems, and will be completed shortly for cryogenic and thermometry. The first studies with this facility, to be started later in FY 1992, will be on the effects of absorbed gas on multipacting and high-field electron loading in low-velocity accelerating structures.

E.2.b. Development of a Superconducting RFQ Accelerating Structure (K. W. Shepard, W. L. Kennedy, \& L. Sagalovsky*)

The possibility of developing a niobium superconducting RFQ and testing it by accelerating a beam from ATLAS has been explored in collaboration with staff members from the ANL Engineering Physics Division. Preliminary numerical modeling indicates that rod-and-post type structures with 4-fold symmetry would combine reasonable mechanical tolerances with a mechanical simplicity that might enable construction of a niobium superconducting RFQ at costs comparable to those for existing superconducting drift-tube structures.

*Engineering Physics Division, ANL.
Tentatively, the proposed superconducting RFQ would be tested by accelerating a low-velocity ($\beta = 0.02$) beam from ATLAS. If such tests were successful, there would be widespread interest because of the need for a high-performance RFQ that can operate in the CW mode.


Argonne has recently entered into a joint project with the Nuclear Science Centre, Delhi, India, aimed at developing improved superconducting resonators suitable for use in a small heavy-ion linac. This linac is needed as an energy booster for ions from a 15-MV tandem. Two staff members from the Nuclear Science Centre are at Argonne studying various possibilities for accelerating structures. This collaborative effort is expected to continue for several years.

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Nuclear Science Centre, New Delhi, India.
III. MEDIUM-ENERGY NUCLEAR PHYSICS RESEARCH AND WEAK INTERACTIONS

In order to understand how to incorporate the quark-gluon structure of the nucleon into a fundamental description of nuclear forces, the medium-energy research program in the Argonne Physics Division emphasizes the study of processes in nuclei in which interactions with the constituents of the nucleon describe the basic physics. Specific research topics include short-range properties of nuclear forces, nuclear pion fields, and quark degrees of freedom in the nuclear medium. Because energetic leptons provide an accurate well-understood probe of these phenomena, primary emphasis is placed on experiments involving electron and deep-inelastic muon scattering.

The medium-energy physics program has a major presence in the research program at CEBAF. Staff members are actively involved in construction of the experimental facilities, and have received approval of five research proposals for measurements when beam becomes available. Members of the group have assumed responsibility for the construction of a broad-purpose short-orbit spectrometer (SOS) to be made generally available to the users at CEBAF. In FY 1991, a preliminary engineering design of SOS was completed; and in September 1991, first funding for component procurement and detailed engineering design was received from CEBAF.

In Fermilab experiment E665, in which Argonne members play an essential role, deep-inelastic scattering of 500-GeV muons has been observed in coincidence with leading hadrons from a variety of nuclei. The very high muon energy and more detailed particle identification distinguish this measurement from previous experiments. The primary objectives of the collaboration are a study of the quark hadronization process and the mass dependence of the quark structure functions. Noteworthy new results include observation of the ratios of xenon to deuterium cross sections down to $x \approx 10^{-5}$, two orders-of-magnitude lower in $x$ than previous results. Nuclear shadowing saturates as $x$ decreases below $x \approx 10^{-3}$ at the value of the ratio of cross sections observed in photoproduction experiments. The rates of two-forward jet events, attributed to photon-gluon fusion and gluon bremsstrahlung, agree with the predictions of QCD. E665 concluded the data-acquisition phase of the experiment in the 1991 fixed-target run. Analysis of the data will continue for at least the next two years.

Much of the technical resources of the lepton scattering program have been devoted to the development of a new target technology which can be used to study elastic electron-deuteron scattering to very high momentum transfer. The tensor polarization of the recoil deuteron in this kinematic region is very sensitive to sub-nucleonic effects in nuclei, most notably meson-exchange and quark effects. A collaboration between the Argonne group and a Soviet group of physicists at Novosibirsk is engaged in a program of tensor polarization measurements. A polarized deuterium gas target intercepting the circulating beam of an electron storage ring is employed and the interactions of the deuterium gas with the circulating electrons are used to study polarization effects in elastic and inelastic scattering. In the initial phase of the program, measurements were completed at moderate momentum transfer. Recently, a more advanced target design was developed at Argonne which will allow extension of measurements to large momentum transfers. The experiment using this design will be performed at Novosibirsk in two phases during the next two
years at the 2.0-GeV VEPP-3 electron storage ring. Work has continued on the development of a high-density laser-pumped source which will be used in the second phase. The program at Novosibirsk provides a proof-of-principle for a proposal to study the spin structure of the nucleon using internal polarized hydrogen and deuterium targets at the HERA electron storage ring. To date, the ANL-Novosibirsk work represents the thickest polarized gas target operating in a storage ring. The Argonne group has the primary responsibility for target-cell design in a broad US-European research proposal for installation of an internal target in the third interaction section of the HERA ring to pursue nucleon-structure studies.

Members of the program continued an active collaboration in the NPAS program at the Stanford Linear Accelerator Center. During 1991, measurements of the photo-disintegration of the deuteron were extended to 4.2 GeV in experiment NE17 in which Argonne provides the leadership. Preliminary results provide strong evidence for the failure of the nucleon-meson description of the reaction and appear to scale in a manner consistent with the quark-parton description of the system. In the companion experiment NE18, a study of quasielastic scattering, measurements have been extended to high values of momentum transfer, never before accessible in (e,e'p) reactions, in a search for color transparency effects. A limited involvement continues in studies at the Brookhaven National Laboratory AGS in exploring global features in relativistic heavy-ion collisions under the conditions of high nuclear densities. Measurements emphasize inclusive spectra of emitted particles and two-particle correlations.

The study of the weak interaction at low energy is the other major component of the medium-energy physics program. The main goals are to verify the implications of the standard model or to discover its inadequacies. The success of the standard model in explaining phenomena over a large range of energies is reflected in the diverse experiments conducted in this program. Experiments to measure quantities important to theories of astrophysics and cosmology form an increasing fraction of the work of this program. An experimental search for neutrino oscillations with a 20-ton active neutrino detector positioned near the LAMPF beam stop is just being completed. The final analysis which provides limits on various modes of neutrino oscillations, as well as rare ion and muon decay modes, are incorporated in a series of manuscripts being submitted for publication. This program is essentially complete.

Neutron-beta-decay experiments at Grenoble have been an important component of the program for some time. This work is being seriously hampered by the temporary closing of the Institute Laue-Langevin reactor. The closing will delay our planned high-precision measurement of the neutron beta-decay asymmetry. New experiments to search for time-reversal violation in neutron beta-decay will begin at the new cold neutron beam at the NIST reactor in Gaithersburg. A method for polarizing neutrons with optically-pumped $^3$He is being developed at Argonne this year.
A new experiment to search for the reported 17-keV neutrino was mounted late last year. This experiment employs a superconducting solenoidal beta spectrometer and a novel technique for reducing the effect of back-scattering. We expect work on this experiment to be an important part of the program this year.

A new experiment utilizing the technique of laser trapping of neutral atoms began this year. The intention is to laser-trap and polarize radioactive $^{21}$Na allowing a precise measurement of the beta-decay asymmetry. This work complements ongoing experiments to study other mirror systems. We began to mount both of these experiments at the Lawrence Berkeley Laboratory 88" cyclotron. The ANL lasers were moved to the cyclotron and work to develop the radioactive atomic beam has begun. The apparatus for the mirror-decay experiment will be set up at Berkeley in the near future.

A new experiment to search for time reversal violation in the beta decay of $^{134}$Cs was begun last year. The Cs will be optically pumped and we intend to measure a beta-gamma correlation following the decay. A Ti-sapphire laser was obtained last year. Work to develop the necessary optical-pumping techniques with stable cesium has started.
A. SUBNUCLEONIC EFFECTS IN NUCLEI

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

(D. Geesaman, H. Jackson, S. Kaufman, E. Kinney, V. Papavassiliou,
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H. Clark, K. Hicks, R. Pinlay,
K. Griffioen, H. Schellman, and P. Spentzouris)

(Text follows on next page)
Deep-inelastic lepton scattering from nuclei provided the first convincing evidence that the structure of nucleons is modified in the nuclear medium. This had profound implications on the understanding of nuclear dynamics. FNAL experiment E665, using the Tevatron II at Fermi National Accelerator Laboratory, provides new information on the nuclear effects on nucleon properties by studying deep-inelastic muon scattering with coincident hadron detection. The key features of this experiment are: 1) An open geometry allowing essentially 4π-hadron detection. 2) A vertex detector system 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 to separate pions, kaons and protons. 5) A muon beam energy of 490 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 x is the fraction of the momentum of the nucleon carried by the struck quark in the infinite momentum frame) and total hadronic energy >25 GeV where there are little data from other deep-inelastic measurements.

The hadron detection provides several important new directions for this research. Studies of the production of two forward-going jets of hadrons offer a sensitivity to the gluon distributions in nuclei. 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 several aspects of the experiment. The first is the management of the on-line data-acquisition software. An integrated system based on the FNAL VAXONLINE and RSXDA products controlled data acquisition from seven CAMAC branches and three FASTBUS segments involving three PDP-11/34 front-end computers, five VMS systems for data concatenation, logging and analysis, and several microprocessors for specific detector monitoring. Argonne is also responsible for a gas-threshold Cerenkov counter, C1, which is required for particle identification in the 5-20-GeV region. Donald Geesaman served as the spokesman for E665 from 1989 to 1991.

E665 first received beam from June 1987 to February 1988. All of the elements of the experiment were brought into operation with the exception of the level-two unbiased trigger. Data were accumulated with a beam-veto trigger at two energies: 490 GeV and 100 GeV on targets of liquid deuterium (luminosities of $2 \times 10^{36}$ and $2 \times 10^{35}$ muon-nucleon/cm$^2$ at the two energies, respectively) and gaseous xenon ($7 \times 10^{35}$ and $2 \times 10^{35}$ muon-nucleon/cm$^2$, respectively). Data at 490 GeV were accumulated on a liquid-hydrogen target ($7 \times 10^{35}$ muon-nucleon/cm$^2$). The first publications of these results are now appearing in the literature. To date, fourteen students have completed PhD theses on this experiment and results have been presented as invited talks at several conferences. The notable results include the first measure of the ratios of xenon-to-deuterium cross sections down to x values of $10^{-3}$, two orders of magnitude lower in x than previous results. It is observed that the shadowing of the nuclear target saturates at $x \approx 10^{-3}$ at the value of the ratio of cross sections.

sections observed in photoproduction experiments. The relative rates of two forward-jet events have been determined to agree reasonably well with those expected from QCD. This is illustrated in Fig. IIIA-1 for the hydrogen data. These two forward-jet events are produced by photon-gluon fusion and gluon bremsstrahlung. Other results include studies of: exclusive vector meson production, measurements of inclusive hadron distributions from deep-inelastic scattering and the way in which these distributions change on nuclear targets, multiplicity distributions, neutral kaon distributions, and low-energy target-fragment proton distributions.

During the 1990 fixed-target run, the collaboration concentrated on more precise comparisons of the nucleus dependence of the structure functions and hadron production. A new target mechanism enabled targets to be changed every minute and a new set of vertex drift chambers was brought into operation to replace the streamer chamber. Neutron counters were added in the backward hemisphere to study the de-excitation of the residual nuclei following deep inelastic scattering. Luminosities of $4 \times 10^{35}$ muon-nucleon/cm$^2$ were accumulated on each of five targets: H, D, C, Ca, and Pb. E665 concluded the data-acquisition phase of the experiment in the 1991 fixed-target run with higher luminosity studies of hydrogen and deuterium with particular emphasis on events with two forward jets of hadrons.

Production analysis of the results of the 1990 and 1991 data will continue for at least the next two years. The Argonne group will concentrate on the 1990 data on nuclear effects in deep inelastic scattering.

![Graph](image-url)

**Fig. IIIA-1.** Forward-jet rates for one jet (open circles), two jets (solid circles) and more than two jets (open triangles) versus $y_{\text{cut}}$ for different $W$ bins (a) $13 \leq W < 18$ GeV, (b) $18 \leq W < 23$ GeV, (c) $23 \leq W < 28$ GeV, (d) $28 \leq W < 33$ GeV). The data have been corrected for acceptance, resolution, and reconstruction efficiency. Lund model predictions are also shown [matrix elements (solid curve) and parton showers (dashed curve)]. The variable $y_{\text{cut}}$ determines the maximum relative invariant mass of hadrons which are combined in forming jets.

\[ZM. \text{Adams et al., submitted to Phys. Rev. Lett.}\]
A high-density polarized deuterium gas target (Phase II storage cell), designed and constructed at Argonne, was installed in the VEPP-3 ring and tests with the electron beam were conducted. Preliminary results indicated that the target has a polarization $P_{zz} = 0.6 \pm 0.2$ and a thickness of $2.5 \times 10^{12}$ nuclei/cm$^2$. With this target, we plan to provide $T_{20}$ analyzing power measurements up to $Q^2 = 15$ fm$^{-2}$. To date, this work represents the thickest polarized gas target operating in a storage ring.

New detectors, provided by Novosibirsk and NIKHEF, were completed and installed at VEPP-3. The background from the new smaller aperture storage cell was found to be larger than expected and the singles rates limit the electron beam current to 80 mA. A collimator system was designed and is being constructed with ultra-high vacuum components from Argonne to minimize this background. With the new collimators, it should be possible to use 200 mA at VEPP-3.

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The laser-driven polarized deuterium source was converted for operation in a high magnetic field in order to overcome radiation trapping effects. With the new source, we have achieved an atomic polarization for deuterium of 42\% with an intensity of $2.1 \times 10^{17}$ atoms/s. An RF transition efficiency of 94\% was measured for the $3^{++4}$ transition in deuterium. With this RF transition efficiency we can expect a $P_{zz} > 0.4$ from the source at $2.1 \times 10^{17}$ atom/s. A schematic diagram of the new source and the polarimeter used for measuring the polarization of the deuterium beam is shown in the left panel of Fig. IIIA-2. Input deuterium molecules are dissociated and the atoms are fed into a spin-exchange cell where the atoms spin exchange with a small admixture (0.3-1\%) of polarized potassium atoms. The potassium is optically pumped by using $\sim 770$ nm light from a Ti-sapphire laser. The polarization of the atomic beam emitted from the spin exchange cell is measured by scanning a compression-tube detector across the focal plane of a sextupole magnet which is aligned with the deuterium beam.

The results for optical pumping with $\sigma^+$, $\sigma^-$ and no laser light are shown in the right panel of Fig. IIIA-2. For $\sigma^+$ light, the deuterium atoms are polarized spin-up with respect to the field direction and the signal at the compression tube is relatively large. For a 100\% polarized spin-up deuterium beam the

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compression tube should show no signal. The results in Fig. IIIA-2 (a) indicate a deuteron polarization of 73% at an intensity of $2.1 \times 10^{17}$ atoms/s. The ratio of atomic-to-molecular deuterium is also measured and taking this into account, the effective deuterium polarization is 42%. The results in Fig. IIIA-2 (b) show that if the same process is carried out at a low magnetic field, then the deuterium polarization is small. This indicates the important influence of radiation trapping at low fields.

Since the publication of these results, the source has undergone steady improvements so that it now delivers a polarization of 40% at an intensity of $4.2 \times 10^{17}$ atoms/s. Further improvements appear possible. A target storage cell is now being designed for use in VEPP-3 to take advantage of the substantial increase in the figure of merit of the new source.

Fig. IIIA-2. Schematic diagram of the high-field optically-pumped spin-exchange source and the polarimeter (a) signal from the scan of the compression tube and detector across the focal plane of the sextuple for $\sigma^+$, $\sigma^-$, and no laser light (b) same as (a) with a 30 G magnetic field.
Photodisintegration of the Deuteron in the GeV Region


The analysis of experiment NE8 at SLAC was completed. The results at $\theta_{\text{cm}} = 90^\circ$ were found to have an energy dependence at the highest energies ($E_\gamma = 1.3-1.6$ GeV) which is consistent with the quark counting rules and the reduced amplitude analysis. The constituent counting rules predict that the cross section $d\sigma/dt$ should have an $s^{-1/2}$ dependence, where $s$ is the total energy in the center of mass. The results for $s^{-1/2} d\sigma/dt$ are shown in Fig. IIIA-3 as a function of photon energy and for $\theta_{\text{cm}} = 90^\circ$, 114°, and 143°. The solid curves are from a meson-exchange calculation by T.-S. H. Lee and the dashed line was drawn to guide the eye. In addition, the data were found to be in disagreement with a meson-exchange model. The data at $\theta_{\text{cm}} = 114^\circ$ and 143° were found to support the trends discovered at $\theta_{\text{cm}} = 90^\circ$. Again at the highest photon energies ($E_\gamma = 1.3-1.8$ GeV), the cross section is consistent with the constituent counting rules. However, this suggestion of scaling extends over a very small range of photon energy. It is important that these measurements be extended to high photon energy (23 GeV) as a more stringent test of the energy dependence of the cross section, since presently the $s$-range where the data are consistent with the quark model is relatively small ($s = 8.5-10$ GeV$^2$). Another important finding is that the cross section at 143° appears to be enhanced relatively to that at 90° by a factor of $\geq 1.5$. This may suggest a large final-state interaction. A manuscript is being prepared for publication.

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Fig. IIIA-3. The quantity $s^{11} \frac{d\sigma}{dt}$ as a function of photon energy at $\theta_{cm} = 90^\circ$, $114^\circ$, and $143^\circ$. 
A.e. Two-Body Photodisintegration of the Deuteron at High Energy:
Experiment NE17 at SLAC (R. J. Holt, K. P. Coulter, D. F. Geesaman,
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Experiment NE17 was granted three days of beam time during the last NPAS run at
SLAC. During that time, the data for the $\gamma d + pn$ reaction were extended up to
2.8 GeV at $\theta_{cm} = 90^\circ$ and up to 4.2 GeV at $\theta_{cm} = 37^\circ$. Data were also taken at
$\theta_{cm} = 37^\circ$, 53$^\circ$ and 90$^\circ$ at $E_\gamma = 1.6$ GeV so that a complete angular distribution
would be available at this energy where an enhancement at a large angle ($143^\circ$)
was found during experiment NE8. At present, the data are being analyzed.
However, a very preliminary analysis has given a much larger than expected
cross section at 37$^\circ$ and at high energy.

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It was discovered in experiment NE8 at SLAC that the differential cross section for the $\gamma d + pn$ reaction at the highest measured photon energies ($E_{\gamma} = 1.3-1.8$ GeV) has an energy dependence consistent with the constituent counting rules and the reduced amplitude analysis. However, the energy range of this result is too small to argue that asymptotic scaling has been achieved. Thus, at CEBAF we have proposed to measure the differential cross section at forward angles for two of the simplest exclusive binary reactions involving a deuteron in the initial or final state: (1) $\gamma d + pn$ between $E_{\gamma} = 1.5$ and 4.0 GeV, and (2) $\gamma d + d^0d$ between $E_{\gamma} = 1.0$ and 3.0 GeV. This proposal was accepted by the CEBAF PAC4.

The constituent counting rules predict an energy dependence of $s^{-11}$ and $s^{-13}$ for the $\gamma d + pn$ and $\gamma d + d^0d$ cross sections, respectively, where $s$ is the square of the energy in the center of mass. Since more complex nuclei involve more constituents and consequently a more rapid fall-off of the cross section as a function of $s$, these two cases may represent the only practical nuclear reactions that can be studied at large values of $s$ where asymptotic scaling is most likely to be observed. These experiments are expected to be practical at high energies since a large beam current (~30 $\mu$A) and a large solid-angle spectrometer (HMS in Hall C) are expected to be available at CEBAF.
A proposal was submitted to CEBAF to measure angular distributions of the proton polarization for the d(\gamma,p)n reaction in the GeV region. This proposed measurement will test the validity of extensions of conventional nuclear-physics theories to the higher energy regime. The results of the experiment will further constrain the suggestions from SLAC experiment NE8 that perhaps asymptotic scaling has been observed above a photon energy of 1.3 GeV. The experiment would make use of a polarimeter installed in either the High Resolution Spectrometer in Hall A or the Short Orbit Spectrometer in Hall C at CEBAF. This proposal was given conditional approval by the CEBAF PAC.

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Proposal to Measure the Spin Structure Functions of the Proton and Neutron at HERA


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

It is absolutely essential to provide accurate measurements for both the proton and neutron spin structure functions in order to settle many of the issues. It is necessary to provide new data for the proton, since the CERN result is only two standard deviations from predictions of the conventional model and the Ellis-Jaffe sum rule. In addition, it is necessary to determine whether or not the simple quark model also breaks down for the neutron. With measurements of both proton and neutron spin-structure functions, it is possible to test the Bjorken sum rule as well. Thus, we have proposed to measure the proton and

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neutron spin-structure functions by using internal polarized H, D and $^3$He gas targets in the 35-GeV HERA electron ring. The storage cell technology for polarized gas atoms which we developed for the Argonne-Novosibirsk collaborative experiment at Novosibirsk (see Sect. A.b.) will be employed at HERA. The experiment will also utilize the longitudinally polarized electrons which are expected to be available in the HERA ring.

A formal proposal for this experiment was submitted to DESY in March 1990. In September 1990 the DESY PRC recommended approval of the proposal with the condition that transverse electron polarization is observed in the HERA ring.

Experiments to measure the transverse electron polarization in the HERA ring were conducted. A polarization of $8 \pm 1\%$ was observed near $E_e = 27$ GeV. Some of the ring elements will be re-aligned before additional polarization measurements are conducted in the Spring of 1992.


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

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

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correct, electroproduction will be suppressed at the lower momentum transfer and enhanced at the higher momentum transfer by multinucleon processes. If on the other hand, as suggested by recent data from Drell-Yan studies of antiquark structure functions, there is no such enhancement, a reformulation of pion exchange models of the medium- and short-range properties of nuclear forces will be required.

A.J. Electroproduction of Kaons and Light Hypernuclei

Since both the electron and $K^+$ are particles that interact weakly, electroproduction of light hypernuclei provides a relatively low distortion means of investigating the fundamental interactions between nucleons, lambdas, and sigmas in few-body systems. In order to perform a detailed investigation of the basic hyperon-nucleon interactions, a proposal to study the electroproduction of kaons in deuterium and other light nuclei was submitted to CEBAF and approved by PAC 5. The particular reactions to be studied are $(e,e'K^+)$ reactions on targets of $^2$H, $^3$He, and $^4$He at incident electron energies near 3 GeV with coincident detection of the emergent $e$ and $K^+$ in the HMS and SOS magnetic spectrometers in Hall C. The residual nuclei will be left in bound or nearly-bound states. In addition to providing new information on the phases and momentum dependence of hyperon-nucleon interactions and measurements of hypernuclear formation, the study will investigate bumps in the cross sections that are anticipated near values of the missing mass that correspond to threshold production of sigmas.

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Information on the propagation of nucleons in the nuclear medium is essential for tests of the nuclear many-body problem and for the analysis of many processes, including pion absorption and inclusive proton scattering. In many instances, proton scattering of a few degrees and energy loss of several MeV is not relevant to the analysis of the fundamental process. Experiment 83-17 is designed to study the macroscopic attenuation of 180 ± 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, and tantalum with a 780-MeV electron beam from the MIT-BATES accelerator. Electrons in the energy range of 545-585 MeV were detected in the OHIPS spectrometer at 50.4° in coincidence with protons in the BIGBITE spectrometer in the energy range of 120-210 MeV and proton angles of 50.1°, 58.2°, 67.9° and 72.9°. The 50.1° proton angle corresponds to the angle for free scattering of an electron with an average three-momentum transfer of 610 MeV/c. Electron singles data were accumulated simultaneously with the coincidence data to provide an independent relative normalization.

The proton transmission is determined by comparing the angular dependence of the ratio of coincidence-to-singles yields to that predicted by a Plane-Wave Impulse-Approximation calculation. Transmissions are compared in Fig. IIIA-4 to recent calculations of S. C. Pieper and V. R. Pandharipande. These calculations show for the first time that the relatively long mean free paths implied by the results can be understood with many-body calculations based on the nucleon-nucleon (NN) interaction. The effects of the density-dependence of the NN interaction and the two-body p-p and p-n correlations are both important in bringing the theory into agreement with the experimental transmissions. The resulting mean free paths for proton propagation in nuclear matter are considerably longer than those expected based on the free nucleon-nucleon cross section, even if Pauli corrections are included, but not quite as long as some optical potentials would suggest.

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Fig. IIIA-4. The experimental transmissions (on a logarithmic scale) for a missing-energy range of 0-80 MeV vs. nucleon number of the target nucleus (on a cube-root scale) are shown including the systematic errors. The lines represent the calculations of reference. The solid curve is the result of the full calculation. The other curves are for the free N-N cross sections (dotted), adding Pauli blocking (dashed) and adding density-dependent effects of the N-N cross section (dot-dashed).
A.2. **Short-Orbit Spectrometer for Hall C**

(H. E. Jackson, D. Potterveld
and B. Zeidman)

An examination of the proposed experimental program for Hall C at CEBAF reveals a major emphasis on coincidence experiments involving a "core" spectrometer and a second arm capable of detecting particles with momenta <2 GeV/c with moderate energy and angular resolution. In most cases, the core spectrometer serves to tag a virtual photon, which induces a reaction in a nuclear target resulting in the ejection of a hadron in the energy range (0.2-2.0 GeV) which is observed in the second spectrometer. Nuclear physics topics addressed in these experiments include color transparency, nucleon propagation, pion electroproduction, and hyperon physics. All of these programs require an acceptance in the hadron spectrometer as large as possible in solid angle and momentum to maximize operational efficiency. In addition, relatively short spectrometer drift lengths are required in experiments involving detection of pions or kaons in order to minimize decay losses. Because the requirements for energy resolution in this class of experiments is moderate, typically ~10^-3, an optimized design with a short optical length less than 10 m will provide a well-matched spectrometer capability. Excellent particle discrimination will be essential for detection of pions and kaons in the presence of high backgrounds. Operation at luminosities as high as 10^{38}/cm^2 sec frequently will be required.

To provide this second arm capability we are building, under contract to CEBAF, a short-orbit spectrometer, the SOS (shown in Fig. IIIA-5) based on a QDD design which has been developed recently at the Los Alamos Meson Physics Facility. The QDD configuration provides a large momentum acceptance, with good energy resolution and solid-angle acceptance in a very compact geometry which can meet the needs of a broad spectrum of studies appropriate for Hall C at CEBAF.

The optical design is point-to-point in both the dispersive (vertical) and the transverse (scattering) planes. For a 1-mm target spot, the first-order resolving power is approximately 2200, while the angular resolution is <2 mr.

Because of the reverse bend in the second dipole, there is a relatively small net deflection of the beam through the spectrometer, a property particularly useful for polarization measurements. Because of the strong edge-focusing, the optical length of the spectrometer is only ~7.4 meters. The rigid structural design, coupled with a compact focal-plane detector package, yields a device that is readily adapted to out-of-plane measurements, if required. Current planning calls for SOS to be operational in early 1994. Operation of SOS in conjunction with the High Momentum Spectrometer in Hall C will provide a coincidence capability with first beams at CEBAF under current planning. The SOS will serve as a general-purpose second arm in a wide variety of experiments planned at CEBAF.
Fig. IIIA-5. Elevation view showing the short-orbit spectrometer (SOS). The spectrometer operating specifications are shown in the inset.
An experiment has been completed at the Stanford Linear Accelerator Center in which measurements of the \((e,e'p)\) coincidence quasielastic cross section in nuclei have been extended to the largest possible \(Q^2\) attainable with the Nuclear Physics Injector and the End Station A spectrometers. Coincidence measurements of the quasielastic \((e,e'p)\) cross section were made on nuclei from carbon to gold in the \(Q^2\) range of 1-7 (GeV/c)^2.

The 1.6-GeV/c spectrometer was used for detection of quasielastically-scattered electrons and the 8-GeV/c spectrometer for recoil proton detection. The 8-GeV/c spectrometer operated in the large acceptance mode which provides 4 msr solid angle for proton momenta up to 5.5 GeV/c. Because of the significant kinematic focusing of the recoil protons which occurs at high \(Q^2\), this allows 100% acceptance of the Fermi cone for \(Q^2 \geq 6\) (GeV/c)^2. The missing energy resolution was 6 MeV at the lowest \(Q^2\) and increased to 25 MeV at \(Q^2 = 7\) (GeV/c)^2. Data were accumulated for hydrogen, deuterium, carbon, iron and gold targets with an average luminosity of \(3 \times 10^{37}\) e-nucleons/cm^2-sec. The beam energy ranged from 2 to 5.8 GeV in measurements of momentum transfers of 1, 3, 5, and 6.8 (GeV/c)^2. Preliminary analysis for the carbon data produced clean missing-energy spectra in which the contributions of the s and p shells could be clearly discerned. The first phase of the data reduction producing preliminary results for all targets will be completed during the summer of 1992. The data obtained at the lower values of \(Q^2\) will be used to test present understanding of quasielastic scattering from nuclei in a conventional nuclear physics picture from \(Q^2 \approx 1\) to \(Q^2 \approx 3\) (GeV/c)^2. At sufficiently high \(Q^2\) there is a striking prediction of QCD for the \((e,e'p)\) quasielastic process in nuclei. At large momentum transfer theoretical considerations suggest diminishing elastic and inelastic final-state interactions of the recoil proton in the nuclear medium as \(Q^2\) increases. This effect is called "color transparency". The data obtained will extend by over one order-of-magnitude the \(Q^2\) range of quasielastic \((e,e'p)\) on nuclei. It will provide new information bearing on questions raised by existing data at low \(Q^2\). It will address the important question of exclusive processes in QCD in its search for color transparency effects at high \(Q^2\).
A proposal was approved by the CEBAF PAC-5 to continue the \((e,e'p)\) studies of proton propagation in nuclei for protons in the energy range of 400-2000 MeV. In this energy range the nature of the N-N interaction changes from elastic to highly inelastic once the pion-production threshold is crossed. The theoretical description of proton propagation also changes considerably from nonrelativistic optical potentials to relativistic potentials to Glauber models. Information on proton propagation in this energy range is quite important to the CEBAF coincidence program. Additionally at the highest energies, manifestations of more exotic mechanisms, such as increased transparency for hard collisions, "color transparency", may become evident.

The experiment will be carried out in the CEBAF Hall C using the HMS 6-GeV spectrometer and the SOS 1.8-GeV spectrometer. Electrons in the quasifree region will be detected in coincidence with protons with missing energies of less than 100 MeV. At two proton energies, \(T_p = 400\) MeV and \(T_p = 1000\) MeV, Rosenbluth separations will be performed to study the A dependence of the longitudinal and transverse coincidence response independently. Since this proposal concentrates on the quasifree region, the projected count rates are relatively high and the background rates are calculated to be quite low, making this an attractive early coincidence experiment for CEBAF.

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Studies of Particle Production at Extreme Baryon Densities Produced in Collisions with Deuteron and $^{28}\text{Si}$ Beams at 14.6 GeV/A


The interaction of relativistic heavy ions with nuclear targets is being studied at the BNL AGS by measuring inclusive cross sections for particles produced ($\pi, K, p$) and two-particle correlations ($\pi \pi, K^+K^+$, and $pp$). The present experiment, E859, is the successor to experiment E802, which completed data taking in 1989. The measurements made by E802 showed that the invariant cross sections for $\pi^+$, $\pi^-$, $K^+$, and $K^-$ are exponential as a function of transverse mass, with slope parameters of $\sim 160$ MeV/c. An enhanced formation of $K^+$ mesons for central collisions of $\text{Si} + \text{Au}$ was inferred from the $K^+/\pi^+$ ratio of 0.2 as compared to the $K^-/\pi^-$ ratio of 0.04 (the $\pi^+/\pi^-$ ratio was 1.0). These results were extended by using a proton beam of the same momentum as the Si beam, with the result that $K^+$ production per projectile nucleon increased going from $p + \text{Be}$ to $p + \text{Au}$ to $\text{Si} + \text{Au}$, while pion production was roughly constant. It has been suggested that enhanced strange-particle production may be a signature of the formation of a quark-gluon plasma in these collisions. However, alternative explanations have been proposed, such as the reaction $\pi^+n + K^+\text{A}$.

Experiment E859 is extending these measurements to a larger kinematic range and will obtain substantially more events by increasing the beam intensity and implementing a second-level trigger. This trigger uses programmable logic modules and fast-encoding TDC's to do particle identification by time-of-flight and momentum, using look-up tables in the logic. In this way one can select relatively rare events for triggering, while rejecting the bulk of the less interesting events. For example, one can identify and accept all $K$-mesons while rejecting the more abundant pions and protons. Similarly, one can identify and accept anti-protons by charge and mass. A two-particle trigger allows selection of pairs of identical particles for measuring the spatial and temporal extent of the interaction region using interferometry (Hanbury-Brown, Twiss effect). Data were taken in June 1990 and February 1991; the final running period is scheduled for March 1992.

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The Argonne contribution to the experiment has evolved as the interests of the members and the needs of the experiment have changed. During E802 we coordinated how the electronic signals from the different detectors were brought into correct timing for the on-line trigger, and worked on the design and implementation of a generalized trigger supervisor. We participated in the calibration and running of the zero-degree calorimeter, as well as in the analysis of the resulting data. We also have been analyzing the data from the target-multiplicity array, and have done Monte Carlo simulations of the response of this array to determine its acceptances for different angular and momentum ranges. For E859 the major task at Argonne has been the development of a computer simulation of the second-level trigger logic. This complex program has aided in the design and debugging of the hardware configuration, and will be used to study the acceptance and efficiency of each trigger scheme in order to properly normalize the results.

B. WEAK INTERACTIONS


LAMPF experiment E645 was a neutrino oscillation search which employed the LAMPF beam stop as a source of neutrinos. Argonne collaborated with other institutions to construct and operate the experimental apparatus which consisted of a 20-ton neutrino detector and a 670-ton active and passive cosmic-ray shield. Data were collected for three years between 1986 and 1989. The experimental work is now completed and the detector was dismantled. The final results of the search for $\nu_e$-appearance arising by oscillations from any of the other three neutrino types ($\nu_e$, $\nu_\mu$, or $\nu_\tau$) produced in the beam dump from stopped $\pi^+$ decay, were compiled for publication. The consequences of a search for neutrino oscillations from the 2% of the neutrinos that come from pions which decay in flight will be published later this year. The E645 active shield, constructed by the Argonne group, was used as an underground muon detector for the CYGNUS extensive air-shower array (see Sec. I.B.b) but it has recently been taken over by the LSND group who are preparing a next-generation neutrino oscillation experiment at LAMPF.

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B.b.  **Search for Cosmic-Ray Point Sources** (S. J. Freedman, A. Zeuli, B. K. Fujikawa, D. A. Krakauer, and the CYGNUS and MILAGRO collaborations)

Our collaborative work with the CYGNUS/MILAGRO group continued this year. The goal is to understand the origin of cosmic rays and specifically to identify sources of ultra-high-energy gamma rays. This research, at the boundary of astrophysics, particle physics, and nuclear physics, is particularly exciting because the few reported point sources have characteristics that are inconsistent with present theoretical understanding.¹

For example, particles that can be attributed to point sources must be neutral, but there is evidence that the particles are neither photons nor any other known neutral particle. If this feature is confirmed in future experiments it will be revolutionary.

We are completing our development of an inexpensive cosmic-ray shower-array counter that could be utilized in an expanded air-shower array at Los Alamos. A paper describing the performance of three liquid-scintillator counters is being prepared. Three of the detectors are constructed of ordinary steel drums (55-, 85-, and 110-gallons) and a fourth is made from a 2-m high PVC tank. Each detector contains a 20-cm layer of liquid scintillator at the bottom and a single photomultiplier at the top. The four prototypes will be operated outside at Argonne again this winter.

The analysis of an all-sky search for "DC" point sources with the CYGNUS array was submitted for publication. There is no evidence for DC sources from either the all-sky search or from 41 interesting astrophysical objects that were specifically considered. The results of a search for periodic point sources are now being prepared for publication. These papers are based on the data collected since the experiment began in 1986.

A detailed proposal for a new array, centered around a 5000-m² pond at Fenton Hill near Los Alamos, was submitted to both the DOE and NSF by the collaboration. When completed MILAGRO will extend the detection efficiency of the present Cygnus array to small showers, generated by primary particles with energies as low as 1 TeV. MILAGRO will bridge the gap between detectors based on the air-Cerenkov technique and present ground-based extensive air-shower arrays which are sensitive above 100 TeV. A small number of water-Cerenkov counters, built with commercial swimming pools, were added to the present Cygnus array to test the feasibility of the MILAGRO scheme. We provided much of the electronics for the water-Cerenkov counters, most of which was designed and built at Argonne. The outcome of the tests with the CYGNUS array support the original plan and progress on MILAGRO continues.

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The most precise values of the weak vector coupling constant $G_V$ now come from $0^+ \to 0^+$ superallowed nuclear beta decay. In principle, the best available transition is the decay of $^{10}$C because the theoretical corrections are small; $^{10}$C is the lowest Z nucleus which has a $0^+ \to 0^+$ superallowed branch. Unfortunately the experimental uncertainty in the branching ratio to the $0^+$ excited state of $^{10}$B is large. We remeasured the branching ratio with the EN tandem accelerator at Western Michigan University in Kalamazoo. An enriched $^{10}$B target was bombarded with 8-MeV protons to produce $^{10}$C. We determined the branching ratio from observations of the cascade $\gamma$ rays with Ge-detectors following beta decay. The crucial $\gamma$-ray efficiency calibration was accomplished with the $^{10}$B(p,p')$^{10}$B$^*$ reaction. By measuring $\gamma$ rays in coincidence with backscattered protons from excitations to the $0^+$ in $^{10}$B, a relative $\gamma$-ray efficiency calibration was accomplished with exactly the same geometry as for the beta decay measurement.

A report of our first measurement was published in 1991 as part of M. Kroupa's Ph.D requirement at The University of Chicago. In a more recent run we obtained enough data to reduce the uncertainty to below 0.2%; these data are being analyzed. Data-acquisition speed is presently the main experimental limitation, but a new system, based on VMI technology was designed and is under construction. We believe the precision can be pushed to below 0.1% with faster data acquisition. This work should elucidate the apparent inconsistency of the present "best" determination of $G_V$ with the constraint that the Kobayashi-Maskawa matrix must be unitary. Unitarity of the K-M matrix is a fundamental test of the presently constructed Electroweak Standard Model.

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The measurement of the beta asymmetry parameters in selected nuclear systems is sensitive to many important properties of the weak interaction. In particular cases, the beta asymmetry is affected by possible and expected induced currents and the strength of the fundamental vector coupling constant. We continue to apply the method of polarizing radioactive nuclei in reactions with polarized projectiles in order to study these effects. These experiments will utilize polarized light-ion beams from the LBL 88* cyclotron.

An apparatus to measure the beta asymmetry in certain mirror systems was built at Argonne. The detector incorporates a large NaI(Tl) detector and two novel plastic scintillator telescopes. The NaI surrounds the target and has inserts for the beta telescopes. Two large coils provide a uniform magnetic field of up

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to $\approx 1.5$ kGauss. The absolute size of the beta asymmetry for mirror decays that have a pure Gamow-Teller transition to an excited state of the daughter will be studied with this system. The excited-state decays are identified by $\gamma$-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 ground-state-to-ground-state asymmetry. Combined with measurements of the beta decay lifetime these measurements can be used to determined $G_Y$ for these transitions. Relatively precise measurements of $G_Y$ in mirror decay have been made previously for the neutron, $^{19}$Ne, and $^{35}$Ar; we hope to extend these measurements to other mirror decay systems.

Our plan to move the apparatus to Berkeley was delayed last year but we expect to begin preparing the experiment at the cyclotron in the next few months.

B.e.  **Nuclear Astrophysics and a Measurement of the D(D,$\gamma$)$^4$He Reaction at the ATLAS ECR Ion Source** (S. J. Freedman, R. Pardo, D. A. Krakauer,* and T. F. Wang†)

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

The first low-beam intensity test runs of the experiment were completed two years ago. Progress on this experiment has been hampered by the unavailability of the ECR source. The problems with the source are now under control and we hope to resume our work this year. The method we are developing should be applicable to measurements of several interesting low-energy reaction cross sections that are important in astrophysics.

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B.f.  A New Measurement of Possible Time-Reversal Non-Invariant Correlations
in Neutron $\beta$-Decay (K. P. Coulter, S. J. Freedman, A. Zeuli, and
B. K. Fujikawa,* with collaborators from Los Alamos, NIST, Harvard, and
the University of Michigan)

The decay probability for polarized neutrons could show a correlation of the
form: $D(J \times P_{e} \cdot P_{p})$. In principle this correlation violates time-reversal
symmetry but final-state interactions, mainly through the weak magnetism effect,
give rise to a non-zero $D$ of about $10^{-5}$. A significantly different value
of $D$ could signal a breaking of time-reversal symmetry. The experimental limits
on $D$ are about $10^{-3}$ from experiments completed more than a decade ago. We
have been planning a new experiment aimed at improving the sensitivity by one to two
orders of magnitude. Last year we joined forces with a Los Alamos group who
have similar intentions. The experiment will be started at the new cold neutron
beam from the NIST reactor in Gaithersburg.

A prototype detector has been constructed and we will begin to prepare for a
beam test in February. A method of polarizing neutrons by passing the beam
through a cell filled with polarized $^3$He will be developed at Argonne. A Ti-
sapphire laser was purchased last year with this in mind.

The observation of time-reversal noninvariance would have an enormous impact on
the physics of the Standard Model. There is some motivation from some versions
of left-right symmetric models that suggests an effect might be observable in
neutron decay.

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B.g.  A Search for a 17-keV Neutrino Emitted in Ordinary Beta Decay
(I. Ahmad, K. P. Coulter, S. J. Freedman, J. Greene, J. P. Schiffer,
A. Zeuli, B. K. Fujikawa,* D. A. Krakauer,† and J. Mortara‡)

One of the most exciting recent developments in nuclear physics comes from
persistent reports of observations of a 17-keV/c$^2$ neutrino. While there is
nothing in the Standard Model to preclude a neutrino so massive, it would be
unexpected and, unless the neutrino has other odd properties, it would be
inconsistent with theories of astrophysics and cosmology. The experimental
situation is controversial. While the massive neutrino is observed to come
from beta decay about 1% of the time in some experiments, others provide
incompatible upper limits on the branching fraction. We have begun a new
experiment at Argonne by exploiting an existing solenoidal beta spectrometer
that is located in the ATLAS experimental area. The magnet was built by a
Purdue group, originally for in-beam experiments.

The half-meter-long superconducting solenoid can produce a 2-Tesla internal
field. With a radioactive source inside the solenoid and a high-resolution
Si(Li) detector in the fringing field, we are making precise measurements of
the beta-decay energy spectrum from the isotope $^{35}$S. The system is calibrated
with various internal conversion sources including $^{109}$Cd and $^{139}$Ce. Our method

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has several advantages over other experiments which attempt to find the discontinuity in an allowed spectra that might signal heavy neutrino emission. No material collimators are necessary. The source strength, and thus the source thickness, can be extremely small. Locating the detector in the fringe field is an effective method for reducing backscattering. In addition, the system is reliably calibrated with conversion lines without the complication of gamma-ray backgrounds.

After insuring and documenting the safety of the apparatus we began to develop the experiment late last summer. We have recently obtained statistically-significant spectra from $^{35}$S and these data are being analyzed for evidence of a 17-keV neutrino. We believe that our method is superior to any of the solid-state detector experiments and that it should help to settle the present controversy.

B.h. Laser Trapping of Radioactive Atoms (K. P. Coulter, S. J. Freedman, L. Young, A. Zeuli, Z. Lu,* B. K. Fujikawa,† S. Q. Shang,† and C. E. Wieman†)

Techniques are now available that allow large numbers of neutral atoms from a diffuse, thermal source to be easily trapped and manipulated with standard lasers. Until recently these investigations have concentrated on the physical processes of the traps themselves, and on simplifying the techniques for loading the traps. Now however, the methods are developed well enough to be utilized in various fundamental experiments.

Two years ago our group set up a facility in the Physics Division to study trapping techniques. We are now applying these techniques to trap radioactive atoms that will be used in fundamental nuclear physics experiments. For the first application, a trapped sample of polarized $^{21}$Na atoms will be used for a precision measurement of beta-decay asymmetry. The physics of the atom trap allows the measurement to be made with very low background, small systematic effects, and a large and well-known nuclear polarization.

The experiment is now being moved to the 88" cyclotron at Berkeley which will be used to produce the radioactive sodium. This experiment is just the first application of this technique which has other obvious applications for measuring correlation coefficients or neutrino mass. Eliminating the systematic errors associated with the typical sources in beta-decay experiments could open up a whole new area of precision measurements.

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B.i. Measurement of Possible Time-Reversal Non-Invariant Correlations in $^{134}$Cs $\beta$-Decay (K. P. Coulter, S. J. Freedman, B. K. Fujikawa,* D. A. Krakauer,† and Z. Lu†)

We have begun an experiment to measure time-reversal non-invariant correlations in the $\beta$-decay of optically-pumped $^{134}$Cs. $^{134}$Cs decay proceeds between two different isospin multiplets and hence the axial vector form factors could contain second-class terms, to which previous measurements were not sensitive. The presence of a term of the form $(J^p \cdot k) (J^p \cdot p \times k)$ in the $\beta$-$\gamma$ cascade of $^{134}$Cs (where $J$, $k$, and $p$ are vectors in the directions of the $^{134}$Cs polarization, the $\beta$ momentum and the $\gamma$ momentum, respectively) would be indicative of $T$ violation in second-class contributions to $\beta$ decay.

The experiment will make use of a closed glass cell containing $^{134}$Cs that can be polarized via optical pumping. Cells have been constructed and will be filled with stable Cs and the appropriate buffer gases. Initial measurements will be made of the polarization and density attainable in such a system and the extent to which the cesium is absorbed by the walls of the cell.

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*B. j. PERKEO II: New Measurements of Neutron Decay Correlation Coefficients (S. J. Freedman, B. K. Fujikawa,* H. Abele,† J. Doehner,† D. Dubbers,† and J. Last§)

In the past ten years the measurements of neutron decay correlation coefficients and the neutron lifetime have improved to the point where they are testing our current understanding of the weak interaction. Interesting discrepancies have appeared at the level of experiments. A small inconsistency between the asymmetry coefficient and the lifetime may be telling us that the weak interaction is not entirely left-handed. These measurements could someday provide the most precise value of the vector coupling constant. At present they give the most precise axial-vector coupling. Our previous experiments with PERKEO at the Institute Laue-Langevin have provided values for the lifetime and the asymmetry coefficient. About two years ago we began to develop an improved instrument for the next generation of experiments. The PERKEO II philosophy is similar to PERKEO I. The electrons from neutron decay are magnetically transported to detectors away from the neutron beam. In PERKEO II the field is perpendicular to the beam instead of parallel. The PERKEO II superconducting magnet is being constructed by Cryomagnetics Inc. in Oak Ridge, Tennessee.

The experiment was to run this year at ILL but damaged parts were discovered and the reactor will be closed until 1994. The ILL facility is the best source of cold and ultracold neutrons in the world; its unavailability is a serious blow to many areas of science. As a consequence we have modified our plans.

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We will prepare to measure the neutrino asymmetry parameter first, before going on to the beta asymmetry parameter. We are in the process of negotiating for possible beam time at two reactors with less intense cold sources, the NIST reactor in Gaithersburg and the new Hahn Meitner reactor in Berlin.

This delay in our plan to make a high-precision measurement of the beta-asymmetry parameter is unfortunate. There are important aspects of the fundamental theory of the weak interaction that would be better understood in the light of more precise experiments.

B.K. The BOREXINO Solar Neutrino Experiment (S. J. Freedman, A. Zeuli, B. K. Fujikawa,* D. A. Krakauer,† and the BOREXINO Collaboration)

BOREXINO is a real-time detector for solar neutrinos with energies above 250 keV. The active element is about 200 tons of ultra-high-purity liquid scintillator viewed by about 1000 8" photomultipliers. The detector would be located in the Gran Sasso underground laboratory. In the context of the standard solar model, BOREXINO would find about 50 events each day from $^7\text{Be}$ neutrinos which are the second most abundant after p-p neutrinos. Measuring the flux of these low-energy solar neutrinos would help elucidate the mechanism responsible for the lower-than-expected flux at both higher and lower energy.

The Argonne group has joined with an international group to help develop the BOREXINO proposal. This year a proposal for a low-level counting facility was approved for installation at Gran Sasso. This facility will help in the development of many of the components of BOREXINO and it will also be useful for measuring radioactive contamination. We expect that this facility will be available to other solar-neutrino experimenters. The BOREXINO proposal was written during 1991 and the final version is now available. It will be submitted to the appropriate agencies in the countries of the collaborating institutions.

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IV. THEORETICAL NUCLEAR PHYSICS

A. NUCLEAR DYNAMICS WITH SUBNUCLEON DEGREES OF FREEDOM

The objective of our research program is to investigate the roles of mesons, nucleon resonances, and quark-gluon degrees of freedom in determining nuclear dynamics.

We are continuing our efforts in developing theoretical models for describing nuclear dynamics in the kinematic regions where the hadronic and electromagnetic productions of mesons and nucleon resonances are important. By carrying out extensive studies of \( ^7N, \gamma N, NN \) and \( ^6d \) reactions over the years, a meson-exchange model with \( \pi \) and \( \Delta \) degrees of freedom has been developed and applied to study various nuclear reactions induced by intermediate-energy hadronic and electromagnetic probes. Our current focus is the development of a theoretical approach applicable to the energy regions accessible to CEBAF and other future experimental facilities, aiming at testing various QCD-based predictions of the excitations of higher mass nucleon resonances \( N^* \).

We applied the light-front relativistic formulation to investigate the electromagnetic nucleon form factors, high-energy photodisintegration of the deuteron, and the spin structure functions of \( ^3He, ^3H \) and the deuteron. We have explored the fundamental problems concerning the connections between relativistic particle quantum mechanics and relativistic quantum field theory. A review article on the null-plane dynamics of particles and fields was completed.

We are studying quark confinement using an approach based on the Schwinger-Dyson equation. Our aim is to develop a practical alternative to lattice gauge theory applicable in investigating the interface between QCD and nuclear physics. A number of studies of QED3 Schwinger-Dyson equations yielded valuable insight into the problem of confinement. We continue to develop an approach for constructing a realistic model of confining quark propagator that can be used in calculations of quantities relevant to nuclear dynamics, such as the pion electromagnetic form factor and the charge symmetry breaking NN forces due to the \( \omega - \rho \) mixing.

We have predicted the effects of color transparency on the \((p,2p)\) reaction at high energies. The consequences of the \( SO(4) \) string-like quark model in determining semileptonic decay of mesons have been investigated.

We are continuing our efforts in investigating \( AN, ANN \) and \( AA \) interactions and their effects on the structure of hypernuclei.

The objective of this work is to develop a theoretical approach for predicting cross sections and spin observables of electromagnetic productions of mesons at energies accessible to CEBAF, aiming at testing various QCD-based predictions of the excitations of the $\Delta$ and other higher mass nucleon resonances $N^*$. Motivated by the existing QCD models of hadrons, we assume that the basic resonant interaction mechanisms of the model Hamiltonian are the absorption and emission of photons and mesons by a bare quark core. The matrix elements of nonresonant interactions are deduced from the low-order Feynman diagrams of an effective Lagrangian. By employing the standard projection operator technique, a set of scattering equations have been derived from the model Hamiltonian. As a first step, we assume that the nonresonant two-pion continuum can be approximated as a fictitious $\sigma N$ state. The scattering equations can then be cast into a set of coupled-channels equations involving only two-particle $\gamma N$, $\pi N$, $\rho N$, $\omega N$, and $\sigma N$ channels, which can be solved by well-developed numerical methods. The bare coupling constants and the range parameters of the form factors of hadronic vertices are adjusted to reproduce $\pi N$ scattering phase shifts up to 2-GeV incident pion energy. We then explore the dependences of the $\gamma N + \pi N$ and $N(e,e'\pi)$ observables on the $\gamma N + N^*$ excitation strengths predicted by various QCD models of hadrons. Some results in $S_{11}$ and $P_{11}$ channels have been obtained. The results for all $N^*$ up to about 2-GeV c.m. energy will be presented in two invited talks at Baryon 92 and photo-nuclear Gordon conferences. A paper will be prepared for publication.

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†National Taiwan University, Taipei, Taiwan, ROC

A.b. **Meson-Exchange Hamiltonian Model with $\pi$ and $\Delta$ Degrees of Freedom** (T.-S. H. Lee, A. Matsuyama,* S. Nozawa,t B. C. Pearce,t and S. N. Yang§)

With extensive studies of $\pi N$, $\gamma N$, $N\pi$, and $\pi d$ reactions over the years, a Hamiltonian model with $\pi$ and $\Delta$ degrees of freedom has been constructed. In 1992, we have accomplished the following work in improving the dynamical content of the model and in applying the model to investigate various reactions involving $\Delta$-excitation and pion production.

The purely phenomenological $\pi N$ interaction of the model Hamiltonian has now been replaced by a meson-exchange model constructed from an effective chiral Lagrangian by using a procedure based on the three-dimensional reduction of the Bethe-Salpeter equation. The resulting $\pi N$ potential includes direct and exchange nucleon terms, $\sigma$ and $\rho$ exchange terms, and direct and exchange $\Delta$ terms. With appropriate choices of form factors, the model can give a reasonable description of $\pi N$ scattering phase shifts. The constructed meson-exchange $\pi N$ model has been used to calculate the effects of $\pi N$ final-state interaction on $\gamma N + \pi N$ reaction. It is found that the results of charged pion

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†Queen's University, Kingston, Canada
‡KFA, Julich, Germany
§National Taiwan University, Taipei, Taiwan, ROC
production processes are comparable to those of earlier calculations using separable πN models. The main improvement is a much better description of the neutral pion production process from threshold to about 400-MeV incident photon energy. The experimental accuracy needed to explore the breaking of chiral symmetry at threshold is illustrated. Two papers describing our results have been published.

We have studied the theoretical problems involved in relating the $\gamma N \rightarrow \pi N$ and $N(e,e'\pi)$ data to the $\gamma N \rightarrow \Delta$ transition form factors. The experimental accuracies needed to explore $\gamma N \rightarrow \Delta$ E2 and charge form factors from $p(e,e'\pi^0)$ spin observables $A_{TL}$ and $A_{TT}$ have been investigated. Our results are illustrated in Fig. IVA-1. We point out the difference between the approach based on the Hamiltonian formulation and the approach currently used by experimentalists in their analyses of $\gamma N \rightarrow N^*$ transition form factors. The results were reported in an invited talk at the 7th Conference of Intersections Between Nuclear and Particle Physics.

The results of our calculation of $\gamma d \rightarrow pp$ reactions are shown in Fig. IVA-2. The $d(e,e'\pi)$ cross sections were calculated and are found to be in good agreement with the data of the Argonne-Saclay collaboration. Extensive predictions of $p(e,e'\pi^0)$ near threshold were made for future experimental tests of chiral symmetry breaking. The results were reported in an invited talk at the 7th Miniconference at NIKHEF.

We have been exploring experimental signatures of the $\Delta$ component in nuclei by considering the electroproduction of pions in $^3$He. The calculation is being carried out by folding the elementary $N(e,e'\pi)$ and $\Delta(e,e'\pi)$ amplitudes into momentum distributions of the nucleon and the $\Delta$ in $^3$He. The final three-nucleon interactions are described by multiple scattering theory. We are in the process of developing a computer program for calculating the $^3$He$(e,e'\pi^\pm)$ cross section and the most interesting triple coincidence $^3$He$(e,e'\pi^\pm p)$ cross section, which, in the quasifree kinematic region, can only originate from the $(\Delta^+NN)$ component in $^3$He.
Fig. IVA-1. The dependence of the $\vec{p}(p,e'\pi^0)$ polarization observables $A_{TL}$ and $A_{TT}$ on the $N + \Delta$ transition strength at $q^2 = -0.2 \ (\text{GeV}/c)^2$. For $A_{TL}$, the solid, dashed and dotted curves are from setting $C_\pi(0)/G_W(0) = 0.15, 0, -0.15$. For $A_{TT}$, the dashed, solid and dotted curves are from setting $G_E(0) = 0, 0.07, 0.15$. $W$ is the $NN$ invariant mass.

Fig. IVA-2. Differential cross section and photon asymmetry at 192 MeV. The data are from LEGS collaborations. The solid curves are from the present calculations using Argonne's $NN$ model. The dotted curves are from the model of Tanabe and Ohta.
A.c. **Null-Plane Dynamics of Particles and Fields** (F. Coester)

Light-front relativistic dynamics is becoming increasingly important for the description of nuclei in the few-GeV region and for the formulation of quark models. A review of theory underlying these applications will appear in the literature. The focus of this review of null-plane dynamics is the fundamental principle of quantum theory that states must form a linear manifold with a unitary scalar product. The intent is to provide an integrated overview over diverse aspects of null-plane dynamics of particles and fields. Hamiltonian particle dynamics is based on the construction of nontrivial representations on finite tensor products of single-particle spaces, and on finite direct sums of such tensor products. The structure of the space of states and the representations of a kinematic subgroup are independent of the dynamics. The dynamics is specified by mass and spin operators which determine the Hamiltonians. These Hamiltonian operators are the Poincaré generators outside the kinematic subgroup. Fock-spaces are infinite direct sums of tensor products of single-particle spaces. The Hamiltonians are integrals of the energy momentum tensor over the null-plane. Fock-space representations of Lagrangian field theories can be formulated as limits of Hamiltonian many-body dynamics. The required cutoff can preserve the symmetry of the kinematic subgroup but destroys the full Poincaré invariance. The nontrivial questions involve the existence of limits as the cutoff is removed. Covariant wave functions arise either as solutions of covariant wave equations, or as matrix elements of products of covariant field operators. The linear manifold of states are equivalence classes of covariant functions. The dynamics appear in the nontrivial inner product and all Poincaré transformations are kinematic. Null-plane restrictions of the covariant functions may provide a unitary map of the covariant constraint dynamics into null-plane Hamiltonian dynamics.


We are investigating the photodisintegration of the deuteron in a light-front impulse approximation. The deuteron is treated as a two-nucleon system. Only one-nucleon currents are included in this exploratory study. The model satisfies the requirements of current conservation and Lorentz invariance. Final-state interactions play an essential role. Preliminary calculations showed encouraging results at high energies. A full calculation is in progress.

*Institute for Theoretical and Experimental Physics, Moscow, Russia*
A.e. **Electromagnetic Nucleon Form Factors** (F. Coester and P. L. Chung*)

We have explored the electromagnetic properties of relativistic constituent quark models of the proton and neutron, in particular their dependence on the constituent-quark mass and the confinement scale. Relativistic effects are never negligible in any model which fits the charge radius of the proton. For a fixed charge radius the confinement scale decreases with decreasing quark masses. Nonvanishing Pauli moments of the constituent quarks are needed to fit the magnetic moments for any value of the quark mass and confinement scale. It is possible to describe existing form factor data at least up to momentum transfers of \( Q^2 = 6 \text{ GeV}^2 \) with quark masses significantly smaller than the conventional nonrelativistic choice of about one third of the nucleon mass. Figure IVA-3 illustrates this result. A paper describing our results has been published.¹

¹North Carolina State University, Raleigh, NC


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![Graph](ANL-P-19,945)

**Fig. IVA-3.** The proton form factor \( F_{1p}(Q^2) \) for different masses and Pauli moments of the constituent quarks. The following line codes are used: dash-dot: \( m_q = .33 \text{ GeV}, F_{2u} = .039, F_{2d} = -.110 \); solid: \( m_q = .24 \text{ GeV}, F_{2u} = -.025, F_{2d} = -.047 \); dash: \( m_q = .21 \text{ GeV}, F_{2u} = -.046, F_{2d} = -.025 \); dots: \( m_q = 0, F_{2u} = F_{2d} = 0 \); dash-double dot: \( m_q = .24, F_{2u} = F_{2d} = 0 \); short dashes: parameterization of Gari and Krumpelmann.
A.f. Spin-Structure Functions of $^3$He, $^3$H and the Deuteron (F. Coester, R. W. Schulze,* and P. U. Sauer*)

The spin-structure functions of $^3$He, $^3$H and the deuteron are related to the spin-structure functions of the proton and neutron, and to the target wave functions by well-defined convolution relations. There are four linear relations between the four spin-structure functions of proton and neutron and the four spin-structure functions of $^3$He and $^3$H. We have derived these relations in detail and numerical calculations have been performed. The results of these calculations show that the relativistic effects are quite small and that nonrelativistic calculations of the nuclear structure effects should be adequate.

*University of Hannover, Hannover, Germany

A.g. Form Factors of Skyrmeons (F. Coester and D. O. Riska*)

In the Hilbert space of the quantum field theory specified by the Skyrme Lagrangian we have constructed a set of translationally invariant coherent states which are eigenstates of spin and isospin. These states, which are functionals of the classical hedgehog fields, provide variational approximations to eigenstates of the mass operator from which Poincaré covariant eigenstates of the four-momentum can be obtained by a well-known procedure. We intend to investigate the relativistic form factors of this model and compare to the form factors obtained in the usual static approximation.

*University of Helsinki, Helsinki, Finland

A.h. On the Implications of Confinement (C. D. Roberts, A. G. Williams,* and G. Krein*)

Some implications of confinement were investigated starting from the basic observation that cross-sections for the production of colored asymptotic states, e.g., free quarks and gluons, from color singlet initial states must be zero if QCD is to be confining. Two pictures of confinement were addressed: the failure of the cluster decomposition property and the absence of a pole at time-like momenta in the propagator of a confined particle. QCD-based models were used as a framework to relate the failure of the cluster decomposition property to other ideas, such as the role of a non-zero gluon condensate. The principal focus of this work was to address the question of the absence of a mass pole through a study of model Schwinger-Dyson equations (SDEs). These equations contain some of the same dynamical information that is present in the study of the cluster decomposition property. The problems with this picture and its study using the Schwinger-Dyson equations were explored. A paper describing this work has been published. These studies are ongoing and will provide the foundation of a covariant, Feynman diagram based, confining quark model applicable to the study of nuclear dynamics.

*Florida State University, Tallahassee, FL
A.i. Electromagnetic Pion Form Factor (C. D. Roberts and C. Holroyd*)

Difficulties associated with a continuation to Minkowski space still prevent a direct evaluation of the form factor using the confining quark propagators of the non-local Nambu-Jona-Lasinio model. A non-relativistic reduction circumvented this difficulty and enabled a one-parameter calculation of the form factor in a model based on realistic quark-gluon dynamics. A calculation of the pion form factor was performed using a non-relativistic reduction of an amplitude obtained from solving the ladder Bethe-Salpeter equation. Excellent agreement was obtained with the experimental data over the entire range available; favorably comparable with the results of more complicated models based on lightcone quantum mechanics. The extension of the approach to other mesons is under consideration. This would serve to delimit the domain of applicability of the non-relativistic reduction. The direct calculation of the impulse approximation Feynman diagrams for this process remains the goal of studies in this area.

*Student, University of California, Santa Cruz, CA

A.j. Light Cone Regular Vertex in Three-Dimensional QED (C. D. Roberts and C. Burden*)

As a step toward understanding the QCD confinement mechanism and gauge parameter dependence of physical observables within the SDE approach, a study of the SDE for the fermion propagator in three-dimensional QED was undertaken. The important new ingredient was an ansatz for the fermion-photon vertex constructed so as to satisfy the Ward-Takahashi identity and to be free of kinematic lightcone singularities. The fermion condensate, which should be gauge parameter independent, was evaluated and a crucial relation between the transverse piece of the fermion-photon vertex and its gauge parameter exposed. This work has been published. The next step in this research is the consideration of the SDE for the photon polarization tensor to address the question of the restoration of confinement through the interplay between singularities in the photon propagator, fermion-photon vertex and the dressing of the fermion propagator.

*Australian National University, Canberra, Australia
A model SDE for the quark self energy in QCD was studied and a solution obtained for both space-like and time-like momenta. The input to the equation was an infrared dominant momentum-space delta function for the model gluon propagator and a quark-gluon vertex that was free of kinematic lightcone singularities and satisfied a Ward-Takahashi identity. The quark propagator was found to have no singularity on the real $p^2$ axis; a result that can be interpreted as a signal of confinement. The importance of this result is that dressing the quark-gluon vertex does not destroy the confinement feature of the delta function interaction. A striking feature of the solution was the cancellation of singularities and zeros between the quark mass function and wave function renormalization which was necessary to ensure confinement. This opens up a wider range of physically motivated models for the quark propagator that can be used in constructing hadron models. A paper describing this work has been submitted for publication. The next phase of this project is to investigate the structure of the propagator in the complex plane; a necessary step before the model can be used in calculations of processes involving on-mass-shell hadrons.

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A.L.  Photon Polarization Tensor and Gauge Dependence in Three-Dimensional Quantum Electrodynamics  
(C. D. Roberts, C. Burden,* and J. Praschifka*)

The photon polarization tensor in QED3 was studied and evaluated using dressed fermion propagators and a fermion-photon vertex that was free of lightcone singularities, satisfied the Ward-Takahashi identity, ensured multiplicative renormalizability of the SDE, and transformed under CPT in the same manner as the bare vertex. The striking result of the calculation was that the inclusion of the dressed vertex and fermion propagator restored confinement to QED3. We also found that photon mass generation via the Schwinger mechanism is not possible when a vertex satisfying the Ward identity is used in the SDE. This makes the Lattice Gauge Theory claims of photon mass generation doubtful. The gauge parameter dependence of the SDE approach was investigated in detail in connection with the Landau-Khalatnikov gauge transformation laws. These transformation laws allow for the complete specification of the gauge parameter dependence of the vertex ansatz which was the last remaining difficulty with this approach to truncating the tower of SDEs. A paper describing this work has been submitted. The next phase of this project is the simultaneous solution of the truncated set of SDEs for the photon polarization tensor and fermion self energy to determine if the conclusions of the preliminary investigations survive the more complete analysis. This would be the first detailed analysis of this set of SDEs and will provide valuable qualitative information about QCD.

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*Australian National University, Canberra, Australia
A.m. **High-Energy (p,2p) Reaction and Color Transparency** (T.-S. H. Lee and G. A. Miller*)

It has been speculated that in the large momentum-transfer region, nuclear medium effects on hadron-hadron interactions in nuclei are negligible. This phenomenon, called color transparency, is predicted by the QCD-motivated consideration that a large momentum-transfer reaction is dominated by a hadron wave function which has a small size in coordinate space, and hence its induced color dipole interaction with the nuclear medium is very weak. Predictions relevant for exploring color transparency in (p,2p) nuclear reactions are often made by using simplified treatments of nuclear dynamics. We examine the extent to which the earlier predictions are valid by carrying out calculations using an improved treatment of the proton-scattering wave functions, nucleon Fermi motion and the effects of long- and short-range nuclear correlations. The consequences of two existing models of color transparency are also predicted. We have found that the calculated transparency for the $^{12}$C(p,2p) reaction oscillates less than the data. A paper describing our results has been accepted for publication.

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*University of Washington, Seattle, WA

A.n. **Nucleon-Nucleon Phase-Shift Analyses in the A-Excitation Region** (T.-S. H. Lee and C. Fasano*)

Within a one-pion-exchange coupled-channels model, we show that the NN inelasticities due to the delta excitation in the $J > 5$ partial waves could significantly affect some of NN spin observables. We suggest that current NN phase-shift analyses should incorporate this theoretical constraint. A paper describing our results has been published. Our higher partial-wave amplitudes are being incorporated into Arndt's phase-shift analysis.

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*University of Pittsburgh, Pittsburgh, PA

A.o. **Study of Semi-Leptonic Decays of Mesons in the SO(4) Quark Model** (T.-S. H. Lee and F. Iachello*)

The parity doubling of hadron spectra implies that the underlying quark dynamics is of SO(4) symmetry. We have calculated the consequences of this dynamical symmetry in determining the semi-leptonic decays of mesons. With the Cabibbo-Kobayashi-Maskawa matrix elements taken from the table of particle data, the predicted semi-leptonic decay rates of D, B and K mesons are in good agreement with the data. A paper describing our results is in preparation.

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*Yale University, New Haven, CT
A.p.  **DWIA Calculations of Pion Absorption on Polarized Nuclear Targets**
(T.-S. H. Lee, M. G. Khayat,* N. S. Chant,* and P. G. Roos*)

Recently, studies of reactions using polarized targets have become possible. Such studies provide a new source of information on the spin dependence of the reaction in the nuclear medium. A number of experiments with polarized targets have been performed or are being planned. As a guide to what new physics might be learned from pion absorption experiments with polarized targets, we have carried out DWIA calculations of the cross sections and analyzing powers for exclusive ($\pi^+,pp)$ reactions on several targets. The calculations use the quasideuteron absorption formalism of Chant and Roos, and the two-body $\pi d + pp$ amplitude from Bugg et al. For $L = 0$ transitions, the target vector analyzing powers are determined solely by the two-body $\pi d + pp$ analyzing power and are small at energies near the $\Delta$ resonance. For the general case of $L > 0$ distortion effects contribute and the analyzing powers can be quite large. A paper describing our results is being prepared.

*University of Maryland, College Park, MD

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A.q.  **Charge-Symmetry Breaking AN Interaction** (A. R. Bodmer and Q. N. Usmani*)

From previous work on the mirror nuclei $^4_1H$, $^4_1He$, we established that the phenomenological charge-symmetry breaking interaction (the difference between the $\Delta p$ and $\Delta n$ 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.

*Jamia Millia Islamia, New Delhi, India
A.r. **A Single-Particle Energies** (A. R. Bodmer, M. Sami,* and Q. N. Usmani*)

We have analyzed the A single-particle energies $E_A$ which have been obtained from $(r^+,K^+)$ and $(K^-,r^-)$ reactions on nuclei with $A = 11$ to $A = 89$. The calculations were made in the Fermi hypernetted-chain approximation which we have developed in earlier calculations. We used a two-body AN potential which has an exchange component, and two different forms for the three-body ANN potential $V_{ANN}$. These potentials were from fits to the $\Lambda p$ scattering, to the binding energies of the s-shell hypernuclei and $^9\text{Be}_A$, and to the well depth of the $A$ binding in nuclear matter. A $A$-nucleus potential $U_A(r)$ is obtained by using a folding procedure which uses the empirical density distribution $\rho_c$ of the core nucleus and also makes approximate allowance for a "fringing field" due to the finite range of the AN force. The $A$ binding energy is then obtained from the Schrödinger equation appropriate for the potential $U_A(r)$ and for an effective mass $M_A$. The results of our analysis show that our previously obtained interactions give a good fit to the data for the exchange parameter $\epsilon \approx .30$ which corresponds to $M_A \approx 0.8 M_A$ for the effective mass at normal nuclear density. Our analysis gives a much improved determination of the $\Lambda p$ p-wave interaction. The strongly repulsive ANN potential is essential for a fit to the data. The well depth is quite accurately determined to be $D_A \approx 28 \pm .5$ MeV. This work is now being completed and prepared for publication. Further developments involve extending our approach to include the effects of the distortion of the core nucleus by the $A$, the inclusion of nuclear matter related rearrangement energy effects, and corrections to the local density approximation.

*Jamia Millia Islamia, New Delhi, India

A.s. **Relativistic Mean-Field Theory of Nuclei with a Vector Meson Self-Interaction** (A. R. Bodmer)

In this work we investigated a one-parameter extension of the standard model of relativistic mean-field theory (RMFT) involving a self-interaction of the vector meson field (denoted by VSI). We showed that such a VSI can give a large softening of the equation-of-state (EOS) of symmetric nuclear matter at large densities $\rho$. A paper describing our results has been published. We have now extended our model to asymmetric nuclear matter for which the neutron density $\rho_n$ is not equal to the proton density $\rho_p$. A one-parameter family of neutron-star EOS consistent with nuclear phenomenology has been obtained. In ongoing work we are applying this family of EOS to obtain corresponding neutron-star configurations, in particular the maximum possible neutron-star mass for any particular EOS.

A.t. **Classical Many-Body Dynamics** (A. R. Bodmer)

We are studying many-particle dynamics based on classical trajectory and/or mean-field approaches. Such methods are of interest both for nuclear collisions as well as for many-electron atoms in intense fields. These studies are a continuation of our earlier work on classical trajectory calculations of high-energy heavy-ion collisions.
B. NUCLEAR FORCES AND NUCLEAR SYSTEMS

Detailed quantitative studies of the consequences of realistic model Hamiltonians for nuclear systems are an important aspect of our work. Our goal is to achieve a description of nuclei from the deuteron to nuclear matter and neutron stars using a single parameterization of the interactions between nucleons, and electromagnetic currents that are consistent with these interactions. This model necessarily contains both two- and three-nucleon potentials and the potentials, of course, contain strong noncentral components. There are two distinct aspects to this work: (1) developing realistic two- and three-nucleon interactions -- the widely used Argonne $v_{14}$ is an example, and (2) developing many-body techniques for computing nuclear properties with such interactions -- our recent computations of the ground state of $^{160}$ and of the capture reactions $^3$He(n,γ)$^4$He and $^3$He(p,ε+ν)$^4$He are examples.

In previous years we have concentrated on variational calculations of the few-body nuclei ($A = 3, 4$) and nuclear matter. We have continued to improve these calculations but we are now devoting most of our effort to nuclei from $^6$Li to $^{160}$, few-nucleon reactions, and electron-induced reactions. We have also begun studies of relativistic corrections and Λ-isobar effects in few-body nuclei, using our nonrelativistic nucleons-only calculations as a starting point and standard for comparison.

The techniques used for $A = 3$ and 4 nuclei can be directly applied to $A = 6-8$, but for heavier nuclei such as $^{160}$ we have had to develop new cluster expansions. These methods are quite successful. We expect that the calculations of heavier nuclei will place significant useful constraints on the choice of the three-nucleon potential.

Much of the quantitative information that will determine the success or failure of competing models of nucleon interactions will come from electromagnetic probes. The Monte Carlo methods that we use make it relatively straightforward to compute the various expectation values required for comparison with electron scattering measurements of form factors, structure functions, Euclidean response knock-out reactions, etc. These calculations are an important aspect of our work.

B.a. Variational Monte Carlo Calculations of Few-Body Nuclear Ground States (R. B. Wiringa and J. Carlson*)

Variational Monte Carlo calculations of $^3$H, $^3$He, and $^4$He are being extended to the study of the five- and six-body nuclei $^5$He, $^6$He and $^6$Li. The variational wave functions include central, spin, isospin, tensor, and spin-orbit two-body correlations and three-body correlations for the three-nucleon potential. They give upper bounds to the ground-state binding energy $\approx 3\%$ above the best Faddeev calculations in $^3$H and the Green's Function Monte Carlo (GFMC) calculations in $^4$He. Current results are shown in Table IVB-I. Electromagnetic form factors are in good agreement with experimental data when two-body currents are included.

*Los Alamos National Laboratory, Los Alamos, NM

TABLE IVB-I

Binding and breakup energies (In MEV) for few-body nuclei, using the Argonne $v_{14}$ two-nucleon and Urbana VII three-nucleon potentials. The 34-channel Faddeev results are from the Los Alamos-Iowa group, and GFMC results are from Carlson.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Method</th>
<th>Binding</th>
<th>Breakup</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>Variational MC</td>
<td>8.25 ± 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>34-ch. Faddeev</td>
<td>8.48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>experiment</td>
<td>8.48</td>
<td></td>
</tr>
<tr>
<td>$^4$He</td>
<td>Variational MC</td>
<td>27.3 ± 0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GFMC</td>
<td>28.3 ± 0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>experiment</td>
<td>28.3</td>
<td></td>
</tr>
<tr>
<td>$^5$He (J=3/2)</td>
<td>Variational MC</td>
<td>25.1 ± 0.1</td>
<td>-2.2 (α + n)</td>
</tr>
<tr>
<td></td>
<td>GFMC</td>
<td>26.8 ± 0.2</td>
<td>-1.5</td>
</tr>
<tr>
<td></td>
<td>experiment</td>
<td>27.2</td>
<td>-1.1</td>
</tr>
<tr>
<td>$^5$He (J=1/2)</td>
<td>Variational MC</td>
<td>24.1 ± 0.2</td>
<td>-3.2 (α + n)</td>
</tr>
<tr>
<td></td>
<td>GFMC</td>
<td>25.5 ± 0.2</td>
<td>-2.8</td>
</tr>
<tr>
<td></td>
<td>experiment</td>
<td>25.8</td>
<td>-2.5</td>
</tr>
<tr>
<td>$^6$Li</td>
<td>Variational MC</td>
<td>27.8 ± 0.2</td>
<td>-1.7</td>
</tr>
<tr>
<td></td>
<td>experiment</td>
<td>32.0</td>
<td>1.5 (α + d)</td>
</tr>
</tbody>
</table>

The study of $^5$He is the study of the low-energy resonances in n-$^4$He scattering, and is being done with both the new variational wave functions and GFMC methods. Using the Argonne $v_{14}$ two-nucleon and Urbana VII three-nucleon potentials, the variational energy difference between the ground state of $^4$He and the j = 3/2 state of $^5$He is 1.0 MeV higher than the experimental difference, while the j = 1/2 state is 0.6 MeV too high, giving about 70% of the observed spin-orbit splitting. The GFMC calculation uses the variational wave function as a starting point and for importance sampling, and requires an order-of-magnitude-more computer time. Current GFMC energy differences with this Hamiltonian are about 0.4 and 0.3 MeV above the respective states, giving about 85% of the spin-orbit splitting.

The studies of $^6$He and $^6$Li are the first to treat them as six-body problems with realistic interactions. The present variational energies of $^6$He and $^6$Li are both 3-4 MeV higher than the experimental values, and 1-2 MeV higher than a separated $^4$He and two-nucleon cluster. Further refinements in the trial wave function and possibly the Hamiltonian will be required to get the additional binding that is experimentally observed. Recent improvements in the computer code (primarily a change from a charge-conserving basis to an isospin-conserving basis) have sped up the $^6$Li code by a factor of 2.5, while reducing its size by a similar factor. This may make GFMC calculations feasible in the future, once a better initial variational wave function is obtained.
A complete description of the three- and four-body work, with some discussion of the five- and six-body problems, was published, and the preliminary five- and six-body results were reported in various conference proceedings.


The methods (Sec. B.a.) used for the few-body nuclei require operations on the complete spin-isospin vector; the size of this vector makes such methods impractical for nuclei with $A > 8$. During the last few years we have developed cluster expansion methods that do not require operations on the complete vector. We use the same Hamiltonians as for the few-body nuclei and variational wave functions whose form is similar to the few-body wave functions. The cluster expansions are made for the noncentral parts of the wave functions and for the operators whose expectation values are being evaluated. The central pair correlations in the wave functions are treated exactly and this requires the evaluation of $3A$-dimensional integrals which are done with Monte Carlo techniques. Most of our effort has been on $^{160}$O and other P-shell nuclei although we have made some calculations of $^{40}$Ca.

In this fiscal year we considered two possible improvements to the variational function that we had previously found for $^{160}$. One of these involved a rearranging (suggested by nuclear-matter studies) of the operators in the two-body correlation. The other was the introduction of a backflow operator in an attempt to improve the density profile (and hence charge form factor) that we obtain. Both modifications, however, resulted in worse variational energies and hence must be excluded. Other, simpler attempts to improve the wave function have also failed and it appears that the $^{160}$O wave function that we have been using for almost two years now is quite good. A complete report on the $^{160}$ work is in preparation.

We have also been making calculations for $^8$He, $^{12}$C, and $^{15}$N. Here we have a number of technical difficulties (possible poor convergence and large Monte Carlo variance) with the cluster expansions that will have to be solved before truly reliable results (of the same quality as $^{160}$O) can be obtained. The simplest case is $^{15}$N because we can treat it as a single-hole state in $^{160}$. Doing so we obtain a very preliminary result for the spin-orbit splitting in $^{15}$N of $6.1 \pm 0.9$ MeV which is to be compared to the experimental value of $6.3$ MeV. This prediction of the spin-orbit splitting based on a realistic Hamiltonian is particularly interesting because $30\%$ of the splitting comes from the three-nucleon potential. Brueckner calculations by Ando and Bando for the Reid potential with a three-nucleon potential give very similar results.

Accurate $^{15}$N wave functions (for the ground state and first $3/2^-$ state) will allow detailed calculations of $^{160}$(e,e') reactions. We have started a collaboration with S. Boffi and M. Radici (Pavia) toward this end. We will be providing the nuclear wave functions, current operators, and the Monte Carlo expansion technique for evaluating expectation values; the Pavia group will be providing the distorted wave functions for the proton-nucleus final state.

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We are investigating the effect of explicit $\Lambda$-isobar degrees of freedom in few-body nuclei. Wave functions with explicit $\Lambda$-isobar components are generated by acting on our standard correlated variational wave functions for the Argonne $v_{14}$ nucleon-nucleon (NN) potential with transition correlation operators that make $\text{NN} \leftrightarrow N\Lambda$ and $\text{NN} \leftrightarrow \Lambda\Lambda$ transitions. The transition correlations are obtained by a fit to exact two-body bound state (deuteron) and low-energy scattering solutions for the phase-equivalent Argonne $v_{28}$ potential, which has explicit $\Lambda$-isobar degrees of freedom.

The wave functions have been used to calculate the $\Lambda$-isobar content and momentum distributions in $^2\text{H}$, $^3\text{H}$, and $^4\text{He}$: 0.5\%, 1.6\%, and 3.1\%, respectively, with a momentum distribution proportional to the D-state in the deuteron, as shown in Fig. IVB-4. Contributions to magnetic moments and form factors in $^3\text{H}$ and $^3\text{He}$, tritium $\beta$-decay, and the low-energy electroweak capture reactions $^3\text{He}(n,\gamma)^4\text{He}$ and $^3\text{He}(p,e^+\nu_e)^4\text{He}$ have also been calculated. The explicit $\Lambda$-isobar components contribute at the one-body level to the electroweak current operators, replacing the traditional effective two-body currents obtained in perturbation treatments. The result is a significantly smaller contribution to both the magnetic form factors and the electroweak matrix elements, and better agreement with data. The electroweak capture calculations (see Sec. B.f) are to be published in Phys. Rev. C.

Ideally, the $\Lambda$-isobar components in $^3\text{H}$ and $^4\text{He}$ should be obtained by solving for the ground-state energy with the Argonne $v_{28}$ (or equivalent) potential directly; we are now investigating the feasibility of such a calculation. However, the present estimates of electroweak effects should already be a big improvement over the traditional perturbative treatment which neglects the kinetic energy of the $\Lambda$-isobar and the renormalization of the nucleonic wave function.

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![Fig. IVB-4. Nucleon and $\Lambda$-isobar momentum distributions for $^2\text{H}$ and $^4\text{He}$.
Error bars show Monte Carlo sampling errors.](image)
Faddeev calculations of $^3\text{H}$ for realistic Hamiltonians containing both two- and three-nucleon potentials appear to be converged to $\sim 0.01$ MeV, while the best variational calculations for the same Hamiltonians result in energies that are $\sim 0.25$ MeV too high. Because the variational wave functions used for larger nuclei have the same structure as those used for $^3\text{H}$, it is reasonable to expect that any improvement in the latter will lead to better variational bounds for the binding energies of larger nuclei.

The Los Alamos-Iowa group has generously provided us with several of their Faddeev wave functions and we have been studying the difference of the Faddeev and variational wave functions. Specifically we are attempting to write the difference as a sum of radial functions times operators acting on the variational wave function. This would provide a correction term that could be used directly in the calculations of larger nuclei. We are considering both two- and three-body non-central operators in the sum.

So far we have managed to reduce the variance in the expectation of the Hamiltonian (an exact wave function has zero variance) but we have not reduced the actual energy. In this regard it is worth noting that the Faddeev wave functions also do not have negligible variance. Work on this problem is continuing.
B.e. Relativistic Effects in Few-Nucleon Bound States
(R. Schiavilla, J. Carlson,* and V. R. Pandharipande†)

To date there have been no relativistic calculations of three-body or larger nuclei using realistic interactions that fit two-nucleon scattering and bound-state data. Relativistically correct expressions for many-body mass operators that use nonrelativistic two-body potentials have been derived, but actual three-body calculations are difficult and have only been done with relatively simple S-wave potentials. In particular, various studies have shown that the relativistic correction terms in such an approach cannot be expanded accurately in powers of \((p^2/m^2)\).

We have initiated a program with an alternative approach to search for relativistic effects in nuclear structure. We have constructed a new two-nucleon configuration-space potential that fits two-nucleon scattering and bound-state data with a Hamiltonian containing relativistic one-body kinetic energies. This potential has the same operator structure and is phase-equivalent to the nonrelativistic Argonne \(v_{14}\) potential, which we will use as a standard of comparison for identifying relativistic effects. The many-body Hamiltonian is then taken as the sum of the relativistic kinetic energy of the individual nucleons and the two-body potentials, supplemented by corrections depending quadratically on the total momenta of the interacting pairs.

The Hamiltonian is being evaluated in both three- and four-body nuclei using variational wave functions and Monte Carlo integration, which has been adapted to give exact expectation values for the square-root kinetic energy. Initial results of this calculation give \(\sim 0.15\) MeV less binding in the triton compared to the nonrelativistic Argonne \(v_{14}\) potential. This difference is of the same sign and magnitude as that found by Glöckle, Lee, and Coester in 1985 using the conventional approach with the nonrelativistic Malfliet-Tjon interaction. We are now proceeding to evaluate the leading correction terms, which we expect to be much smaller than those found in the conventional approach. We then expect to study other bound-state properties such as momentum distributions, electromagnetic form factors, two-nucleon distribution functions, etc.

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B.f. Nuclear and Neutron Matter Studies (R. B. Wiringa)

Nuclear and neutron matter remain an area of continuing interest. A major study of the dense nucleon matter equation of state, neutron star properties, and nucleon optical potential, for realistic Hamiltonians including three-nucleon (NNN) potentials, was completed in 1988. This work, coupled with our studies of finite nuclei, showed that the addition of plausible NNN potentials can make a significant improvement in calculated binding energies and saturation properties. However, the relatively simple three-nucleon potentials used to date cannot give detailed agreement for both finite systems and nuclear matter at the same time. Recent work has concentrated on generalizing the matter codes to study a wider range of possible three-nucleon potentials. We are also now adding three-body correlations for the three-body potential, which have proved to be important correlations in finite nuclei. New NNN potential models are expected to result from our studies of p-shell nuclei (see Secs. B.c and B.d) and their consequences for nuclear matter and neutron stars will be evaluated promptly.
Two other areas of future work in nuclear/neutron matter are also contemplated, depending on progress in lighter systems. The investigation of relativistic effects in few-body nuclei (Sec. B.e) might be extended to matter, but the algorithm for evaluating relativistic kinetic energy will need some modifications. The relativistic corrections would be of particular interest for dense matter and neutron stars.

The influence of explicit Δ-isobar degrees of freedom (Sec. B.c) might also be studied. In principle, an interaction like the Argonne v_{28} model should include many effects commonly subsumed in NNN potentials. A significant effort was made to calculate nuclear matter saturation for the Argonne v_{28} interaction several years ago with disappointing results. However, the studies of Δ-isobars in few-body nuclei employ a new variational ansatz that could significantly improve the matter results. It would also be useful to have an optical potential for Δ-isobars in matter for studies of high-energy heavy-ion collisions.

E.g. **Nuclear Transparency** (S. C. Pieper and V. R. Pandharipande*)

A calculation of the transparency of nuclei to intermediate-energy nucleons from (e,e'p) reactions was made and compared to results from a Bates experiment. The calculation can be divided into two principal steps. In the first the mean free path of nucleons in nuclear matter is computed as a function of the nuclear matter density. This calculation is made using experimental differential cross sections corrected for Pauli blocking and non-locality effects (effective-mass corrections). In the second step, a local-density approximation is used to compute the probability that the recoiling nucleon is absorbed as it travels through the nucleus. Because the recoiling nucleon was part of the original nucleus, the correlated density of the remaining nucleons with the initial position of the struck nucleon must be used. The measured transmission is computed by averaging the absorption probability over the nuclear density.

The calculations were made for recoiling 180-MeV protons. The computed mean-free paths were found to be in good agreement with other more sophisticated calculations. The predicted transmissions are in excellent agreement with the data (Fig. IVB-5). The Pauli blocking, effective mass corrections, and correlation effects are all of comparable importance.

This work has been published.¹ We are now extending the calculation to higher energies for comparison with an ANL experiment at SLAC and proposed CEBAF experiments. An interesting preliminary result is that Pauli blocking continues to be important in the 1-2-GeV region because of the very pronounced forward-backward peaking of the elastic cross sections.

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Fig. IVB-5. The transparency of various nuclei plotted as a function of the rms radius of the nucleus. From the bottom the curves were obtained by using free cross sections (dash-dot-dot), and by adding Pauli blocking (dash-dot), $m^*/m$ corrections (dashed), and pair correlations [Eq. (3.5)] (solid). The recoiling proton energy is 182 MeV.

B.h. **Few-Body Electroweak Capture Reactions** (R. Schiavilla, R. B. Wiringa, J. Carlson,* V. R. Pandharipande,† and D. Riska‡)

Variational Monte Carlo methods have been used to make ab initio calculations of the low-energy capture reactions $^3$He(n,$\gamma$)$^4$He, and $^3$He(p,$e^+\nu_e$)$^4$He. These reactions have very small cross sections in impulse approximation (IA) due to the near orthogonality of the scattering and ground states. Consequently exchange-current corrections play an important role in both reactions, and an accurate evaluation of their contributions requires knowledge of the two-body correlations in the system. Previous theoretical work used shell-model wave functions for the ground states of $^3$He and $^4$He, but we have good correlated wave functions for both the ground state of $^4$He and the 3+1-body scattering states, which reproduce the experimental scattering lengths.

The $^3$He(n,$\gamma$)$^4$He cross section was measured recently by the Argonne weak interactions group and a Dutch group to be 54-55 $\mu$b. Our IA calculation gives only 6 $\mu$b, while "model-independent" exchange currents raise this to 72 $\mu$b. Our initial estimates of "model-dependent" exchange currents pushed the total cross section to 112 $\mu$b, with a large contribution from $\Delta$-isobars. A subsequent improvement in the treatment of $\Delta$-isobar terms (see Sec. B.e) has reduced this result to 86 $\mu$b. This final value is sensitive to the (poorly known) n+$^3$He scattering length, and could vary from 60-110 $\mu$b as the scattering length is varied within its experimental limits.

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The reaction $^3\text{He}(p,e^+\nu_e)^4\text{He}$ is the source of the highest-energy neutrinos in the sun, and an accurate estimate of the astrophysical S-factor would be valuable for new solar-neutrino detectors that are being developed. The IA gives an S-factor of $6.9 \times 10^{-23}$ MeV-b. Axial exchange currents are all "model-dependent" in this case, but are fixed by fitting the Gamow-Teller matrix element for tritium $\beta$-decay. Here they cancel against the IA value to reduce the S-factor to $1.4 \times 10^{-23}$ MeV-b. There is again a significant sensitivity to the $p + ^3\text{He}$ scattering length, with a $\pm 20\%$ variation possible within the experimental errors. The initial calculations were published in 1990-91 and the improved treatment of $\Delta$-isobar contributions has been submitted for publication.

B.i. **Electromagnetic Response and Spectral Functions of Few-Body Nuclei**

(R. Schiavilla and J. Carlson*)

A Green's function Monte Carlo (GFMC) method has been developed to calculate, in an exact fashion, the imaginary-time (Euclidean) proton response function of few-body nuclei. This quantity is related to the Laplace transform of the longitudinal response function measured in inclusive electron scattering experiments, and can therefore be compared to data. The method is conceptually simple, and does not require knowledge of the continuum spectrum. It has been successfully tested in the deuteron for a realistic potential (the Argonne v$_8$ model) for which the Euclidean response can be calculated exactly in the conventional way by solving for the scattering states of the Schrödinger equation.

The four-body calculations, the only ones completed to date, are also based on the Argonne v$_8$ potential, supplemented by the Urbana VIII three-nucleon potential, and an exact GFMC ground-state wave function. The results compare very favorably with those obtained by Laplace-transforming the available $^4\text{He}(e,e')$ longitudinal data from Bates and Saclay. Calculations for the three-body nuclei are in progress, and a paper is in preparation. The method can be very easily generalized to compute the Euclidean transverse response, as well as to investigate the effects due to two-body components in the electro-excitation operator on these response functions. It should also be possible to use it for studying the imaginary time spectral function of the three- and four-body nuclei. See Figs. IVB-6 and IVB-7.

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Fig. IVB-6. The Euclidean proton response of $^4$He calculated with the Green's Function Monte Carlo method is compared with the Bates and Saclay data.

Fig. IVB-7. The longitudinal response function of $^4$He obtained with the GFMC method is compared with data and with a PWIA calculation.
B.j. **Ground State of Hypernuclei** (S. C. Pieper and Q. N. Usmani*)

The variational Monte Carlo calculation of nuclei (Secs. B.c and B.d) is being adapted for hypernuclei such as $^{\Lambda\Lambda}_A$, $^{\Lambda_\Lambda}_A$, and $^{\Lambda_\Lambda}_C$. In this calculation we will use the same realistic nuclear Hamiltonians we use for normal nuclei with the addition of phenomenological NA and NNA potentials such as those studied previously by Bodmer and Usmani. The wave function will also be of the same form as in normal nuclei with additional NA noncentral correlations.

The development work for these calculations is being done principally by Usmani and his collaborators at Jamia Millia. We anticipate that final production calculations will be done on the NERSC computers. Usmani spent two months each summer at Argonne during 1990 and 1991 learning our Monte Carlo methods and doing test calculations of lambda matter drops. Pieper spent three weeks in New Delhi in early 1992, and exchanges are expected to continue. At present, two-body cluster calculations with central AN correlations have been implemented in the program. Work on noncentral clusters and higher-order clusters is proceedings. Travel and living expenses are being provided by an NSF grant.

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B.k. **Theory Institute on the Nuclear Hamiltonian and Electromagnetic Current for the 90's** (S. C. Pieper, R. Schiavilla, and R. B. Wiringa)

This Institute, which was supported with Physical Research Program Administration funds, brought together 27 researchers from outside Argonne (and about 8 from Argonne) to discuss nuclear Hamiltonians and the associated electromagnetic currents that should be used in computations of nuclear properties in the present decade. Most of the physicists attended a one-week conference in August, but three were here for periods of up to a month to collaborate with us. The talks at the conference were very lively and demonstrated that much remains to be done in this area and that there is much interest in finding realistic Hamiltonians and currents that can be used in the types of calculations we do.

C. **HEAVY-ION INTERACTIONS**

Our heavy-ion studies concentrate on applications of the coupled-channels model to investigate reactions near the Coulomb barrier. Our objective is to provide a consistent, unified, quantum-mechanical explanation of various phenomena which are currently being measured experimentally, such as sub-barrier fusion reactions, polarization effects in elastic and inelastic scattering, compound nucleus spin distributions, and transfer reactions. The channels considered consist of inelastic states in both projectile and target, and of channels in which a few nucleons are exchanged between projectile and target. We do not use imaginary potentials since we try to account explicitly for the total reaction cross section. Nuclear structure considerations are clearly important in choosing the channels to include, and we attempt to see the effects of nuclear structure on the measured cross sections. We are active both in developing new techniques and applying them to analyze experimental data from ATLAS and other heavy-ion facilities.
C.a. Elastic Scattering and Fusion Calculations of $^{160} + 63,65\text{Cu}$

(H. Esbensen, S. Landowne, and S. H. Fricke*)

We have analyzed fusion and elastic scattering data for $^{160}$ on $63,65\text{Cu}$ within a coupled-channels approach, including the most dominant reaction channels due to inelastic excitations of the low-lying $2^+$ and $3^-$ states in both projectile and target, and one-proton stripping process. It has recently been suggested that the data for these systems show unusual isotope and energy dependences. Our analysis shows that one can explain the isotope and the energy dependence of the measured fusion and elastic scattering data separately but not simultaneously. The fusion and the elastic scattering data appear to be shifted systematically by 2 MeV with respect to each other. This shift is significantly larger than the uncertainty in the energy scale for the fusion data, which is of the order of 1 MeV. This work has been submitted for publication.

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C.b. Coupled-Channels Calculations with Full Angular-Momentum Coupling

(H. Esbensen and S. Fricke*)

In a new generation of coupled-channels calculations we would like to focus on specific reaction channels, which cannot be described as single-step processes. In order to make a realistic calculation of the angular distributions for such channels it will be important to include the full effect of angular-momentum couplings, which we avoided in our previous studies of fusion and elastic scattering by using the rotating-frame approximation. We have therefore developed computer programs that can handle inelastic excitations and one-nucleon transfer channels simultaneously, with the full effect of angular-momentum couplings included. We plan to apply these programs to analyze inelastic scattering and transfer data, and to include the effect of higher-order processes in our calculations.

C.c. Reactions of $^{160}$ with Samarium Isotopes

(H. Esbensen)

We performed coupled-channels calculations of $^{160}$ scattering on different samarium isotopes, at energies near the Coulomb barrier. We have, in particular, calculated the spin distributions for fusion and made comparisons to gamma-multiplicity measurements for $^{160} + 152\text{Sm}$. This work has been published.

In order to test our calculations in more detail, we also analyzed the data from a complete measurement of the fusion and elastic scattering of $^{160}$ on $144\text{Sm}$. The data have been fitted previously using complex, energy-dependent optical potentials. Our calculations, which make use of an energy-independent ion-ion potential and include couplings to the low-lying $2^+$ and $3^-$ states in both projectile and target, reproduce the data quite well. Moreover, the energy dependence of the measured inelastic excitations is also reproduced.
D. NUCLEAR STRUCTURE STUDIES

The goal of this program is to interpret and predict various properties of nuclei with models using effective two-body interactions to produce correlations in the nuclear eigenstates. This is carried out in close contact with experimental programs.

A major effort is the investigation of superdeformation at both high and low spins, using states in a deformed potential with the possible addition of a one-body cranking term. Our prediction of a new region of superdeformation in the vicinity of $^{192}$Hg was confirmed by Argonne experiments and has been widely studied since then. One feature found is the smooth increase of moments of inertia with increasing angular momentum. We find that this trend can be obtained by using a pairing interaction which goes beyond the quasiparticle approximation.

Observation of superdeformed states in isotopes of Pb not predicted by the cylindrically symmetric Strutinsky calculations has led us to consider changed single-particle potentials and unusual shapes such as the $Y(3,1)$ shape (banana). This has led to new minima in the energy surfaces often with lower energies than previously obtained. Such studies require larger bases for calculation but are needed to understand nuclear properties.

A continuing study concerns the properties of nuclei far from the valley of stability. Many experiments are investigating the properties of $^{11}$Li, and we have formulated a model with a $^9$Li core and two loosely-bound neutrons. A Green's function technique allows calculation of the interaction of these neutrons using states going far into the continuum and resulting in a barely-bound nucleus. We can then exhibit the spatial correlations of the neutrons as well as the response of $^{11}$Li to external probes, for comparison with observations.

D.a. Superdeformed and Hyperdeformed Banana-Shaped Nuclides Near $A = 190$ (R. R. Chasman)

Although our calculations correctly predicted the accessibility of the superdeformed states in $^{191}$Hg and $^{192}$Hg, they also indicate that the superdeformed minimum is well above yrast in nuclides such as $^{194}$Pb and $^{196}$Pb even at angular momentum of $I = 40$. Nevertheless, superdeformed states have been found in these nuclides. We have explored one possible explanation of this observation by considering new deformation modes that could lower the energy of the superdeformed minimum.

We consider the banana-shaped $Y(3,1)$ deformation mode which connects states that differ by two quanta in the $z$-direction and one in the perpendicular direction. The shapes that one gets from this mode are quite extended. As the surface is large, the liquid-drop model suggests that this mode could exist in heavy elements where large decreases in Coulomb energies balance an increased surface energy. Carrying out calculations in the Hg region, we have found new minima in the energy surface at moderate values of the quadrupole deformation, and fairly large values of the $Y(3,1)$ deformation. These minima lie below the axially-symmetric superdeformed minima for nuclides with $Z > 80$. In the Hg ($Z=80$) isotopes, the two minima are roughly degenerate at high spins.
There is an interesting technical problem with cranking nuclear shapes having banana deformations. The preferred axis for cranking is the y-axis, rather than the x-axis which is typically the case. This means that in addition to losing all of the symmetries that allow us to break the Hamiltonian into blocks, we must deal with a complex Hamiltonian. We have modified our program to handle complex Hamiltonians. Our first study of the banana minimum has been published.

D.b. **Choice of Oscillator Basis for Banana-Shaped Nuclides**
(R. R. Chasman)

One of the unexpected results from the calculation of states in the banana-shaped minimum is that the resulting quadrupole moments are the same as those of a purely quadrupole deformed shape with $\nu_2 \sim 0.8$. This result is obtained by summing proton single-particle quadrupole moments and by calculating the quadrupole moment of the liquid-drop shape. Our findings suggest that an oscillator basis having a deformation different from the quadrupole deformation of the shape parameterization would be useful in Strutinsky calculations. We have carried out several calculations to find a reasonable prescription for the choice of basis deformation. We find that a very good choice of quadrupole moment for the basis is one with the same sum of quadratic moments as the shape of interest. We anticipate that this prescription will prove useful for the study of other deformation modes. Using this choice of oscillator basis, we found that the shell corrections associated with the largest banana-shaped deformations that we studied are reduced considerably. This has the beneficial effect of increasing the barrier of the banana minima against fission. The calculated quadrupole moments in these minima are reduced by ~20% relative to our previous estimates. The effects of additional deformation modes on the banana minimum remain to be explored.

D.c. **The Parameterization of the Single-Particle Potential**
(R. R. Chasman)

One possible explanation for the production of superdeformed states in the Pb isotopes is that an alternate parameterization of the single-particle potential provides a more realistic description of nuclear structure than the potential we have used. One such description that has been found to be successful in the heavy elements is the Rost potential. The novel feature of this potential is a proton spin-orbit radius that is $3/4$ of the central field radius. We have carried out a set of Strutinsky calculations using the Rost potential for protons. We find that the superdeformed wells are substantially deeper with this potential than with the conventional one. However, we find that the superdeformed states in $^{194}$Pb and $^{196}$Pb are still well above yrast at $I = 40$. It seems worthwhile to continue the exploration of the effects of alternate potential parameterizations. These results have recently been published.
D.d. The FDSM and Superdeformation Near A = 220 (R. R. Chasman)

A most interesting prediction of the fermion dynamic symmetry model (FDSM) is the existence of oblate superdeformed states in nuclides with 84 < Z < 90 and 124 < N < 130. Based on these predictions, we have carried out Strutinsky-method calculations of energy surfaces for nuclei in this region. We do not find oblate superdeformed minima in precisely this region, but we do find oblate superdeformed minima in slightly heavier nuclei. This region of oblate superdeformation is centered at 225Am; i.e. Z = 93, N = 125. This is in rather good agreement with the FDSM predictions. The oblate minima are at 7-MeV excitation energy at I = 0, and remain above 6 MeV relative to yrast even at I = 40. We have examined the approximations made in the application of the FDSM to the heavy elements and find several reasons for quantitative differences between the Strutinsky and FDSM approaches. We have also studied prolate superdeformation in this region. Here, the prolate superdeformed minima are somewhat lower in excitation energy, ~4 MeV at I = 0. The minima are quite deep; 2-3 MeV at I = 0. Unfortunately, the prolate superdeformed states do not become yrast at high spin; in fact, the excitation energy increases slightly with increasing spin. This will make the prolate superdeformed states hard to populate.

D.e. Single-Particle States in the Heaviest Elements
(I. Ahmad, R. R. Chasman, A. M. Friedman,* and S. W. Yates†)

The search for superheavy elements has been a major theme of nuclear structure research for the past twenty years. Theoretical predictions of the stability of superheavy elements depend crucially on the single-particle energy level spacings in the vicinity of 114 protons and 184 neutrons. The approach that we are taking is to learn as much as possible about these levels from spectroscopic studies of nuclides in the A = 250 region. This is possible because there are members of the relevant spherical multiplets that drop rapidly in energy with increasing deformation, and are fairly close to ground states in the strongly deformed nuclides near A = 250. The orbitals that are important for fixing the shell corrections near N = 184 are the h11/2, j13/2 and k17/2 spherical states. For each of these spherical orbitals, there is a corresponding deformed orbital whose energy in the A = 250 region is quite sensitive to one of these spherical states, e.g. the 1/2+[761] orbital that has already been identified in 251Cf is quite sensitive to the spherical j13/2 orbital. The position of the 1/2+[880] deformed orbital is very sensitive to the k17/2 spherical state. According to our calculations, this state should be found at ~1500 keV in 251Cf and should be populated in a one-nucleon transfer reaction using an (α, 3He) reaction. We have calculated signatures for the low-lying states in 251Cf and the calculated energies and signatures are in good agreement with the experimentally observed (d,p) spectrum. We expect to see the high-j states in a (α, 3He) study. Our analysis of low-lying states in 251Cf has been published. The (α, 3He) experiment has been approved.

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D.f. Rotational Bands with Identical Transition Energies in Actinide Nuclei (I. Ahmad, M. P. Carpenter, R. R. Chasman, R. V. F. Janssens, and T. L. Khoo)

We found that the phenomenon of identical moments of inertia is not unique to superdeformed bands. The transition energies in the ground-state rotational bands of $^{240}$Pu, $^{244}$Cm, $^{246}$Cm and $^{250}$Cf are essentially identical up to $I = 8$. Unfortunately, the ground-state bands are not known in these nuclides at higher spins. In $^{238}$U and $^{238}$U, however, the ground-state rotational bands are known to high spins. Here, the differences in transition energies are less than 2 keV up to $I = 24$; and the average value of this energy difference is less than 1 keV. This has led us to look for similarities in the level structures of the superdeformed $d_g$ isotopes and the deformed $U$ isotopes. We note that there are large gaps in the single-particle spectra, in both cases, just before the region of identical bands. Further, we find that the single-particle orbitals, obtained in a cranking calculation, above this gap typically have small values of the alignment. This is not strictly true in the actinide case, where the $7/2^-[7/2]$ and $1/2^+[6/2]$ orbitals have moderately large alignments individually. However, their alignments are opposite in sign and the two levels fill together, so the net effect is a small alignment. This work has been published.1


D.g. Nuclear Equilibrium Shapes Near $A = 100$ (R. R. Chasman)

We have carried out a study of the $A = 100$ mass region using the Strutinsky method. Our calculations show that the equilibrium deformations are quite large for these nuclides at $I = 0$ when pairing forces are neglected. If one uses the usual values for pairing interaction strengths, one finds that these equilibrium deformations are reduced considerably; even in those nuclides where large equilibrium deformations are known to be present from experiment. To deal with this discrepancy, we reduced the pairing interaction strength by 25% from the values used in the rare earths and actinides. This reduction in pairing strength gives reasonable agreement between experiment and theory for those nuclides where ground-state rotational bands are known. Because the nuclides in this region are strongly deformed, the valence nucleons have a large probability of being in regions of low density. Detailed spectroscopic studies should provide information on the effective pairing interactions. Studies involving a density-dependent pairing force will be needed as more experimental data become available. Our studies of the actinides suggest that a density-dependent pairing interaction provides a better description than a constant-pairing force. In the calculations that we have carried out only a constant-pairing force was used.

The calculations show a large new region of strongly deformed nuclides that may be experimentally accessible. The calculations also show a large region of triaxial nuclides ($\gamma = 30^\circ$) for $41 < Z < 47$ and $66 < N < 72$. A very interesting feature of the $A = 100$ mass region is a predicted decrease in equilibrium deformation with increasing angular momentum. The predicted deformations are $\nu_2 \sim 0.35$ at $I = 0$ and $\sim 0.20$ at $I = 20$. Recent experimental studies of transition lifetimes by the groups in Jülich and Budapest provide some evidence for a decrease in deformation with increasing spin. Our results have been published.
D.h. **Many-Body Wave Functions** (R. R. Chasman)

In the past few years, we have developed many-body variational wave functions that allow one to treat pairing and particle-hole two-body interactions on an equal footing. By using residual interaction strengths (e.g., the quadrupole interaction strength) as generator coordinates, one gets many different wave functions; each having a different value of the quadrupole moment. These wave functions are particularly useful when one is dealing with a nucleus that has several different minima in the energy surface, such as in the Hg isotopes where there is a superdeformed minimum in addition to those at small deformation. Because the same basis states are used in the construction of the many-body wave functions for all values of the quadrupole moment, it is possible to calculate overlaps and interaction matrix elements for the many-body wave functions (which are not in general orthogonal) fairly easily. With the product structure of our wave functions, it is possible to include all particle-hole configurations with a fixed value of $J_z$ in the many-body variational wave functions. The variational wave functions contain a large number of single-particle basis states. In our first calculations of transition matrix elements for all values of the quadrupole moment, it is possible to calculate overlaps and interaction matrix elements for the many-body wave functions (which are not in general orthogonal) fairly easily. With the product structure of our wave functions, it is possible to include all particle-hole configurations with a fixed value of $J_z$ in the many-body variational wave functions. The variational wave functions contain a large number of single-particle basis states. In our first calculations of transition matrix elements in the Hg region, we used a basis consisting of all spherical proton orbitals with $40 < Z < 126$ and all spherical neutron orbitals with $70 < N < 184$. In spite of the large size of this basis, it appears that it is not large enough. We can effectively increase the size of this basis, by constructing basis states that are linear combinations including single-particle states from many higher shells. In this way, we retain the important feature of orthogonality of basis states. We do however give up the orthonormality of our basis functions, for different values of the generator coordinate. The extension of our many-body code to accommodate this feature implies a major coding effort. We have started this effort.

D.i. **Angular Distribution of Neutrons Emitted in $^{11}$Li,$^{9}$Li Breakup Reactions** (H. Esbensen)

We have studied the angular distribution of neutrons emitted in Coulomb-induced breakup reactions. This is a dominant reaction mechanism for the breakup of neutron-rich nuclei on a high-$Z$ target. It is demonstrated that the angular distribution of neutrons is closely related to the shape of the low-lying dipole response. This is illustrated for $^{11}$Li,$^{9}$Li reactions on Au which have recently been measured. Here we have adopted an independent particle description of the valence neutrons in $^{11}$Li, and we obtain good agreement with the data. This implies that the predicted shape of the associated dipole strength in $^{11}$Li is reasonable at low excitations. This work has been published. The effect of pair correlations on the dipole response and on the angular distribution of the emitted neutrons is an important issue which has been investigated separately.

D.j. **Soft Dipole Response of $^{11}$Li** (H. Esbensen and G. F. Bertsch*)

We have studied the effect of pair correlations on the low-lying dipole response of $^{11}$Li. This is a continuation of a previous study (which has now been published) of the ground state and the binding of neutron-rich nuclei which can be modeled as an inert core plus two interacting valence neutrons.

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*Michigan State University, East Lansing, MI*
We have developed a Green's function technique to solve the 3-body Hamiltonian equation, both for bound states and for states in the continuum, in particular for the continuum dipole states that are generated by Coulomb excitations of the ground state.

We have previously calculated the dipole response from the correlated ground state of $^{11}\text{Li}$, ignoring the interaction between the two neutrons in their final state. Our present study shows that the final-state interaction modifies the dipole strength function substantially, making it similar to an independent particle strength function, but the total dipole strength is enhanced by 50% due to ground-state correlations.

The dipole strength is concentrated in a peak just above threshold, and it is consistent with the energy dependence of the Coulomb dissociation cross sections that have been extracted from measurements of the $(^{11}\text{Li},^{9}\text{Li})$ fragmentation on high-Z targets. The shape of the threshold peak is consistent with the narrow component of the measured neutron angular distributions. Moreover, it is also consistent with the longitudinal momentum distribution of the residual $^{9}\text{Li}$ nucleus, which has been measured recently. This work has been submitted for publication.

D.k. **Angular Correlations of Neutrons Emitted in $(^{11}\text{Li},^{9}\text{Li})$ Reactions**

(H. Esbensen and G. F. Bertsch*)

We have investigated the angular correlations between the two neutrons emitted in $(^{11}\text{Li},^{9}\text{Li})$ reactions that are induced by the Coulomb field from a target nucleus. Our calculated angular distributions of neutrons emitted in $(^{11}\text{Li},^{9}\text{Li})$ Coulomb-induced reactions show a surprising anticorrelation. It favors an emission with a large opening angle between the directions of the two neutrons in the rest frame of $^{11}\text{Li}$. Another interesting feature is the correlation between the kinetic energies of the two emitted neutrons. It exhibits a ridge structure, which reflects the shell structure of the unstable nucleus $^{10}\text{Li}$. Thus, if the energy of one of the two neutrons is large, the most likely kinetic energy of the second neutron is close to the energy of the neutron resonance in $^{10}\text{Li}$. Some of our results have been submitted for publication. Related 3-body coincidence measurements have now been performed at several laboratories, but the data have not yet been fully analyzed. We intend to complete our study by analyzing the new coincidence data when they become available.

*Michigan State University, E. Lansing, MI*
D.2. Effects of Correlations on $^{11}\text{B}(\pi^-,\pi^+)^{11}\text{Li}$ Reactions (H. Esbensen, D. Kurath and T.-S. H. Lee)

The double charge exchange (DCX) reaction $^{11}\text{B}(\pi^-,\pi^+)^{11}\text{Li}$, provides an alternative probe of correlations between the valence neutrons in $^{11}\text{Li}$. We have performed a distorted-wave impulse approximation calculation of this reaction by assuming that $^{11}\text{Li}$ consists of a $^9\text{Li}$ core plus two valence neutrons. The ground state has been determined previously by diagonalizing a 3-body $^9\text{Li}$-n-n Hamiltonian, which includes an effective n-n interaction. We determine the $^{11}\text{B}-^9\text{Li}$ two-proton removal amplitudes from shell-model calculations. The most dominant amplitudes, relevant to the DCX reaction, have the total angular momentum $J = 0$ and 2, whereas the ground state of the two valence neutrons in $^{11}\text{Li}$ has $J = 0$. Our results show that the effect of correlations between the two valence neutrons is to increase the forward-angle DCX cross section by a factor of 2 to 3, compared to an independent particle description. This increase improves the comparison to the data considerably (see Fig. IVD-8). We have also studied the dependence on the choice of the pion optical potential and the sensitivity towards the binding energy of $^{11}\text{Li}$. Our results are in good agreement with the data from a recent measurement. A paper describing our results is in preparation.

![Fig. IVD-8. Angular distribution of pions emitted in $^{11}\text{B}(\pi^-,\pi^+)^{11}\text{Li}$ reactions. The independent particle model of $^{11}\text{Li}$ (IPM) underestimates the data by a factor of 3.5. The results obtained from the 3-body model, for a two-neutron separation energy of 0.2 MeV (fully drawn curve), 0.34 MeV (dotted), and 2 MeV (dotted-dashed), are in much better agreement with the data.](image-url)
D.m. Features of Li Isotopes (D. Kurath)

The use of radioactive beams has made possible the study of nuclei away from the valley of stability. For example there is now extensive knowledge of the Li isotopes from \( A = 5 \) to 11. Large neutron excess affects the beta-decay process in that states with very large Gamow-Teller strength become energetically available. Quantitative measurements are difficult because the final states are usually unstable to emission of neutrons and tritons. These nuclei have been studied with the shell model which gives an excellent representation of the low-lying states. There is large GT strength in the region where experiments locate it, but at present not as much is observed as is calculated. In a recent experiment with a \( ^{8}\text{Li} \) beam on C and Au targets,\(^1\) the first excited state of \( ^{8}\text{Li} \) was populated and the transition strength extracted under the assumption of E2 multipolarity. The resultant BE2 value is an order-of-magnitude larger than one calculated even with the usual out-of-shell enhancement common in the \( \text{lp} \) shell. It is more likely that this is an M1 excitation since the gamma decay gives one of the strongest BM1 values known (1.5 W.U.), in agreement with the shell model. The M1 possibility is mentioned by the experimentalists, but they did not have the spin-dependent optical potential needed to extract a value.

ATOMIC AND MOLECULAR PHYSICS RESEARCH

Atomic Physics research in the Physics Division consists of four principal ongoing programs:

(1) Atomic physics at ATLAS,
(2) Fast ion-beam/laser studies of atomic and molecular structure,
(3) Interactions of fast atomic and molecular ions with solid and gaseous targets,
(4) Synchrotron-based atomic physics.

The program at ATLAS focuses principally on atomic structure studies. The work aims at testing relativistic and quantum-electrodynamical (QED) many-body interactions in terms of atomic energy levels and their decay rates. There is a continuing close collaboration with atomic theorists (primarily from other institutions) especially those performing calculations of few-electron systems. Our measurements on lifetimes and wavelengths in one- and two-electron systems constitute high-precision studies of highly charged ions. Some of the work is part of collaborations with university personnel [Notre Dame, Toledo, Bochum (Germany), Grenoble (France), and Texas A&M] and NIST research groups. Our grazing-incidence monochromator has been equipped with a position-sensitive detector. As well as enhancing the rate of data collection in spectroscopic measurements, this detector allows us to utilize the pulsed time-structure of the ATLAS beam thereby reducing significantly the background levels observed in the search for very weak decays. Another two-dimensional position-sensitive detector is being mounted on a normal-incidence monochromator.

Studies of atomic collisions using ATLAS beams have included three experiments. Two of these use the full ATLAS system to study dielectronic recombination (DR) and resonant transfer and excitation (RTE). Our recent studies confirm the unexpectedly narrow resonances that we observed previously in DR measurements from channeling in thin gold crystals. Before the accelerator closure in October 1990, the ECR source intended for the new ATLAS injector provided low-energy beams for electron-spectroscopic studies of electron-pickup interactions, plus a precision laser-spectroscopy study of QED and relativistic corrections in two-electron boron. Analyses of these experiments continue.

The program of Coulomb-explosion studies of small molecular-ion structures continues to use the Dynamitron accelerator. We have made the first measurements utilizing our newly developed pulsed molecular-ion jet source. Successful tests using simple molecular ions, e.g. $\text{He}_2^{++}$, demonstrated the effectiveness of cooling within the source. The group has now begun measurements of structures of some cooled light diatomic and triatomic ions.
High-precision laser excitation of fast-ion beams at the BLASE facility continues, with the emphasis this year on studies of hyperfine structure of metallic and rare-earth ions. New theoretical developments in this area have shown greatly improved comparisons between our measured and calculated hyperfine constants. Previous relativistic Hartree-Fock calculations sometimes differed by an order of magnitude or even in sign, whereas new calculations show agreement mostly to within 10%. Several new measurements are in progress to test the new methods of calculation.

Several members of the group have begun a program of synchrotron-based atomic physics measurements as part of a lab-wide initiative in support of the Advanced Photon Source (APS). The latter is now under construction and is expected to be available for experiments at the end of 1995. The initial goal is to gain staff expertise in this exciting new area of X-ray atomic physics. There is strong overlap between the goals of our ongoing ATLAS experiments testing relativistic atomic structure, and X-ray interactions with relativistic inner-shell electrons of heavy atoms. Thus, we have collaborated with several University and National Laboratory groups in experiments mainly at the Brookhaven National Synchrotron Light Source (NSLS) X-ray ring. The expertise of one of our staff members, especially in X-ray optics and crystal spectroscopy, gives an additional breadth to this program.

The theoretical program continues as a series of visiting theorists, plus active collaborations through other mostly university-based theoretical groups.
V. FAST ION-BEAM/LASER STUDIES OF ATOMIC AND MOLECULAR STRUCTURE

Our principal goals in this program involve high-precision spectroscopic measurements of structures in ionic species. Experimental studies of this type provide the most stringent tests of ab initio calculations of atomic and molecular structure. The BLASE facility provides a well-controlled environment in the production of ions of very well-defined velocities. We take advantage of the speed of the ions to make almost Doppler-free measurements using collinear laser-excitation techniques. The extraction of ions from the discharge ion source and the subsequent formation into an ion beam provide a collision-free environment in which to make precision measurements.

In the past year, we have used the BLASE facility to make measurements of hyperfine structure (hfs) in low-lying states of singly-ionized $^{49}$Ti. These studies are motivated by the very recent theoretical developments at Michigan Technical University which, using relativistic many-body methods, have shown promise of an ab initio understanding of hyperfine structure. Specifically, that many-body formalism has yielded very good agreement (better than 14%) with our previously measured hfs constants for nd $^3$D states in Sc II and Y II, whereas earlier multiconfiguration Dirac-Fock (MCDF) calculations were unable even to determine the correct sign! These studies represent a major advance in the theoretical treatment of hfs, which we plan to guide to more complex systems with our measurements. In this direction, we have made optical and radiofrequency measurements on 12 states arising from the $3d^3$, $3d^2$4s and $3d^2$4p configuration of $^{49}$Ti$^+$. The final analysis is underway. Preliminary comparisons with values generated by the Michigan group show that the level of perturbation necessary to explain the Sc II and Y II results is insufficient for the Ti II system.

During this period, we have also finalized the analysis of the fine and hyperfine structure in $^{14}$N$_2^+$, the first molecular ion in which the laser-rf double resonance method was applied. This technique produced an improvement in resolution of a factor of 500 over the previous laser spectroscopic measurements and permitted the first determination of four molecular constants, including the quadrupole coupling constant, eq$Q$. A paper was published jointly with a group at the University of Western Ontario who had obtained complementary data.

Our experimental program in r.f./laser studies of small molecules using thermal neutral and slow-ion beams ended at the beginning of 1990. The concluding work and data analysis are represented by three publications. Further analysis is continuing on other experimental data.
Building on our previous studies of hyperfine structures of transition metal ions, we have progressed to a system with slightly higher complexity, three electrons outside a closed shell rather than two. Motivation for these studies stems partly from the outstanding theoretical agreement (better than 14%) obtained by a group at Michigan Technical University with our previous measurements on the effective two-electron systems, Sc II and Y II.

We have made optical and radiofrequency measurements of hyperfine structure in 7 low-lying metastable levels arising from the 3d³ and 3d²4s configuration in ⁴⁹Ti II. An example of a radiofrequency resonance is shown in Fig. V-1. Laser-induced fluorescence data have been acquired for 5 upper levels in the 3d²4p configuration. An example of a laser-induced fluorescence spectrum is shown in Fig. V-2. Preliminary analysis and comparison with calculations from the Michigan group reveal that, for states where many-body effects are large, the same level of theory used for Sc II is insufficient to explain the hfs in Ti II.

The final analysis of experimental data is currently underway. In addition, the Michigan group is currently refining their calculations by including higher-order excitation.

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ANL-P-20,557

![Graph](image-url)

Fig. V-1. An example of a laser-rf double resonance spectrum from ⁴⁹Ti⁺, 3d³ ²P₃/₂ level. The line represents a fit to the Rabi two-level flopping model. The FWHM is determined by the transit time through the rf interaction region and is 734 kHz.
Fig. V-2. The upper curve shows the experimental laser-induced fluorescence spectrum of the \(3d^3\ 2G_{9/2} - 3d_{4p}^4\ 2F_{9/2}\) transition. The lower curve shows the calculated spectrum using the A and B values obtained from a combination of the lower state rf data and this optical spectrum.

b. **Laser-rf Double Resonance Study of \(N_2^+\)** (N. Berrah-Mansour,* L. Young, C. Kurtz, T. Steimle,† and G. L. Goodman,‡)

The nitrogen molecular ion, whose optical spectrum was first observed in 1858, is one of the most thoroughly studied of diatomic molecules, owing to its importance in atmospheric phenomena, yet it was only in 1982 that an optical linewidth sufficiently narrow to resolve the hyperfine structure was achieved by means of collinear ion-beam laser spectroscopy. In spite of the high resolution of this optical experiment, it was impossible to directly determine ground-state intervals in this molecular ion until the current experiment using the laser-rf double-resonance technique. In general, the problem of direct determination of ground-state intervals in molecular ions has been a significant challenge to experimentalists for well over a decade, resulting in the development of both direct absorption and double-resonance methods.

We have applied the laser-rf double-resonance method to a molecular ion for the first time. In combination with a set of complementary data from the University of Western Ontario, fifty-six hyperfine components of fine-structure transitions \(|\Delta J| = \pm 1\) were measured in rotational levels from \(N = 1\) to \(N = 27\) of the \(v' = 1\) vibrational level of the \(X^2E_g^+\) ground state of \(^{14}N_2^+\). In order to fit the data we required seven molecular constants, corresponding to the following interactions: electron spin-rotation fine structure and its centrifugal distortion, Fermi contact hyperfine structure (hfs), dipolar hfs and its centrifugal distortion, and electric quadrupole and nuclear spin-rotation hfs. Table 1 shows the present results, as well as all results obtained previously using optical spectroscopy. A paper has been published.¹

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†Arizona State University, Tempe, AZ.  
‡Chemistry Division, ANL.  
TABLE V-I. Fine and hyperfine constants of the $X^2\Sigma^+_g (\nu^* = 1)$ level of $^{14}\text{N}_2^+$. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theory (MHz)</th>
<th>Experiment (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present work</td>
<td>Gottscho et al.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Miller et al.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rosner et al.</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>&lt;360.</td>
<td>270.(150)</td>
</tr>
<tr>
<td></td>
<td>276.92253(13)</td>
<td>259.(7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>279.1(6)</td>
</tr>
<tr>
<td>$\gamma N$</td>
<td>-3.9790(23)$\times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$b_F$</td>
<td>91.</td>
<td>100.6040(15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105.(4)</td>
</tr>
<tr>
<td>$t$</td>
<td>27.</td>
<td>28.1946(13)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49.(6)</td>
</tr>
<tr>
<td>$t N$</td>
<td>-7.35(27)$\times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$e_{Q}$</td>
<td>0.7079(60)</td>
<td></td>
</tr>
<tr>
<td>$c_I$</td>
<td>0.01132(85)</td>
<td></td>
</tr>
</tbody>
</table>

The two-electron atom is one of the simplest many-body systems available for testing our understanding of relativistic quantum mechanics. The lack of a complete Hamiltonian to describe the bound states in such a system leads to the need to solve the relativistic correlation between the two electrons and the quantum electrodynamic (QED) correction perturbatively; a challenging theoretical problem. Recent advances have improved theoretical calculations to the 2-parts-in-$10^6$ level for the $1s2s \, ^3S_1 - 1s2p \, ^3P_{0,1,2}$ transitions in two-electron boron, the system under study.

We have made precision wavelength measurements of these transitions in helium-like boron using laser excitation in a fast beam extracted from the ECR source. The measurements are precise to 2 parts in $10^7$ of the transition energy and test these most recent calculations at a level of 0.1% of the Lamb shift. The measurements, similar to previous measurements in helium-like lithium, show a deviation of more than 1σ theoretical uncertainty. A paper has been published.\(^1\)

d. **Laser-rf Double Resonance Measurements Using Thermal Beams**  
(W. J. Childs and Y. Azuma)

Rf double-resonance measurements and analysis in diatomic molecular systems and neutral atoms were completed during this year:

We studied the spin-rotation and hyperfine structure of the $X^2\Sigma^+$ state of YS. This work investigates in detail the anomalously negative spin-rotation constant in the radical YO when the oxygen is replaced by the chemically equivalent S atom.

Doppler-free laser spectroscopy of CeF was used to observe its hyperfine structure. This study was carried out to allow comparison of the structure of CeF with the previously studied isoelectronic diatomic PrO. Although hyperfine structure was observed for the first time in CeF, it is not directly comparable to that in PrO since the sites of the interactions are on opposite sides of the molecule in the two cases.

We used rf double-resonance spectroscopy to determine the ratio of the static nuclear magnetic-octupole moments for the (nuclear) ground states of $^{151}$Eu and $^{153}$Eu. The ratio was measured independently with the Eu atoms in several different atomic states and self-consistency was observed. No theoretical evaluation of the ratio is yet available. The J-dependence of the hyperfine anomaly was also measured, as were the surprisingly large effects of second-order hyperfine interactions between different electron configurations.

Work is also in progress on the analysis of rf double-resonance measurements of the hyperfine structures of $^{143,145}$Nd I and in Tb I. A review of laser-radio frequency double-resonance studies of atomic, molecular and ionic beams is also near completion. The review describes the techniques and experimental results in detail in order to pinpoint the interesting areas remaining to be exploited and to compare present theory and experiment.
VI. INTERACTIONS OF FAST ATOMIC AND MOLECULAR IONS
WITH SOLID AND GASEOUS TARGETS

Tightly-collimated beams of molecular ions with energies adjustable in the range 0.5-9.0 MeV are directed onto thin (~30 Å) foil or gaseous targets. The distributions in laboratory velocities are measured with high resolution (~0.005° and ~200 psec) for the resultant ions. The major aim of the work is a general study of the interactions of fast ions with matter, but with emphasis on those aspects unique to the use of molecular-ion projectiles. In particular, we have been able to deduce the structures of the incident molecular ions. These different aspects of the work are mutually interdependent. In order to derive structural information about a given molecular ion, one needs to know details about the way the dissociation fragments collectively interact with the target in which the dissociation occurs. Similarly, a knowledge of the structure of the incident molecular clusters is important in understanding the physics of their interactions with the target.

Our work therefore began with careful studies involving beams of simple, well-known molecular ions (HeH+, etc.). Even with these, several new and interesting phenomena were encountered (e.g., the interactions between the molecular constituents and the polarization oscillations that they induce in a solid target, the marked differences in dissociations induced in gases as compared with those in foils, the anomalously high transmission of some molecular ions through foils, and striking electron-capture phenomena when compared to atomic ions). Now that those studies have elucidated the important physical processes affecting the penetration of molecular ions through matter, we have concentrated our efforts on using this knowledge to study the structures of the molecular-ion projectiles. The development of multiparticle detectors has enabled us to measure directly the densities of atomic nuclei within small polyatomic molecules.

Our recent efforts have been devoted primarily to the development of a new ion source for vibrationally-cold molecular ion beams. In addition, as a result of anomalies observed with ultrathin targets, studies of secondary electron emission were also carried out.


An important advance this past year was the continued development, and operation in the Dynamitron high-voltage terminal, of a supersonic expansion source of vibrationally cold molecular ions. This source (see Fig. VI-1), which consists of a pulsed-jet supersonic gas expansion crossed by a beam of ionizing electrons, had presented a major technological challenge because of the requirements of pumping background gas from the high-voltage terminal in order to achieve the high stagnation pressures necessary for vibrational cooling. During the previous fiscal year, that goal was achieved by the installation and successful stable operation of a specialized 330-1/sec turbomolecular pumping system in the strong rf-fields of the terminal. During the past year, modifications to the gas-exchange system were carried out which have extended the operable stagnation pressures to as high as 4 atmospheres. Test experiments were carried out with several diatomic molecular ions (He₂⁺, H₂⁺, and N₂⁺) which indicated successful vibrational cooling as evidenced by the bond length distributions measured by Coulomb-explosion techniques.
Utilizing beams from the new ion source, we have re-investigated the bond-length distribution within $\text{He}_2^+$. By turning off the pulsed jet and forming the molecules by electron impact on the stagnant background gas, we were able to replicate our earlier results (obtained with an rf discharge source) indicating an extremely hot vibrational distribution. This distribution can be fitted with a broad inverted (non-thermal) vibrational state population.

In contrast to those results, when the molecules are instead formed in the supersonic expansion, there is rapid vibrational cooling (see Fig. VI-2). With stagnation pressures as low as 50 mTorr, we already observed vibrational-state populations which are dominated by the ground state. There is evidence for some additional further cooling for stagnation pressures up to 2 atmospheres, but the vibrational population is essentially already equilibrated with the $\nu = 0$ fraction in excess of 90%. Indeed, the dominant portion of the distribution can be well-fitted by a pure ground-state distribution. Under this assumption, we have deduced the $\nu = 0$ wave function from the data and from it both the internuclear potential energy and zero-point energies. These results are in excellent agreement with ab initio theories of this very simple diatomic molecular ion.

While we do not yet fully understand the origin of the tails of the measured distribution, if we assume that they are entirely due to the excited-state population, then the data imply a vibrational temperature lower than 80 meV. This beam clearly represents the coldest vibrational-state population ever obtained with a nuclear accelerator at such high kinetic energies and is extremely promising for our future work.

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*Graduate Student, University of Illinois, Chicago, IL.
Fig. VI-2. The "cold" experimental kinetic energy distribution (points with error bars) is shown in (a). A line has been added to this distribution to guide the eye. The "hot" experimental kinetic energy distribution (points with error bars) is shown in (b). Also shown in (b) for comparison is the smoothed "cold" kinetic energy distribution from (a) (solid line) renormalized to the number of counts in the "hot" distribution.

c. **Electron Loss to the Continuum by Molecular Ions Traversing Ultrathin Targets** (T. Graber,* E. P. Kanter, Z. Vager, B. J. Zabransky, and D. Zajfman)

Because of the success of the supersonic-expansion source, we have for the first time been able to unambiguously separate "Coulomb-explosion" effects from structure effects. This has proved extremely important in ascertaining the role of post-foil effects which have previously been hinted at by experiments, but which have been difficult to disentangle. For the highest beam energies (and thinnest targets), our measurements with helium dimer ions fragmenting to bare alpha particles have demonstrated clear evidence of post-foil screening effects. As a result, we sought to understand what role the presence of convoy electrons might play in affecting fragment motion outside the foil.

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*Graduate Student, University of Illinois, Chicago, IL.
Measurements of convoy electrons were carried out in coincidence with Coulomb-explosion fragments. We found no evidence for any difference in the kinetic energy distributions for those fragment ions accompanied by convoy electrons as compared to those which emerge from the target without such electrons. Our measurements of the absolute yield of convoy electrons produced by molecular projectiles were in good agreement with previous experiments. With H$_2^+$ ions, and using our ultrathin Formvar targets, we were able to extend those yield measurements to the extreme non-equilibrium region near the expected peak of the yield. In this regime, we found the yield to be of the order of $10^{-4}$ electrons/molecule, in good agreement with theoretical expectations. This yield is clearly too small to account for the measured Coulomb-explosion anomaly.
VII. THEORETICAL ATOMIC PHYSICS

Our theoretical program currently consists of a series of visiting theorists. J. Sapirstein of the University of Notre Dame continues to collaborate with us on the relativistic structures of three-electron and other relativistic atomic systems.

R. Stephen Berry of the University of Chicago collaborates principally in the theoretical interpretation of measurements in the Coulomb-explosion program.

Peter Sigmund (Odense University) visited Argonne in January 1991 and in January 1992 to continue his term as an Argonne Fellow, working on the theory of the mean free path of energetic electrons and positrons in solids, and other atomic collision phenomena (also with H. Esbensen, a nuclear theorist in the Physics Division).

L. J. Curtis of the University of Toledo continues to collaborate both on the experimental part of our ATLAS program and on the theory of allowed and forbidden atomic decay processes.

Donald Beck of Michigan Technical University has been a close collaborator on the atomic hyperfine structure measurements at BLASE and provides theoretical calculations which help in the analysis of the observed transition frequencies.

a. Scattering and Stopping of Swift Molecules under Coulomb Explosion
(P. Sigmund*)

The scattering and stopping of the fragments of a fast diatomic molecule under Coulomb explosion have been analyzed theoretically. The central assumption in the scheme is the dominance of the Coulomb explosion, while electronic stopping (including wake forces) and elastic scattering are treated as perturbations. Charge exchange has been neglected.

Coulomb-explosion images obtained with solid targets display significant distortions. For small penetrated-layer thicknesses, the images appear contracted in the direction of the molecular axis, and expanded perpendicular to it. This distortion is described quantitatively by a linear transformation.

General expressions have been derived for the effect of continuous and stochastic forces on the distribution of fragment velocities from Coulomb explosion (the "ring pattern"). Moreover, relations have been found that allow one to scale velocity distributions valid in the absence of Coulomb explosion into distributions allowing for Coulomb explosion.

The work finds application in describing the shift in ring patterns due to electronic stopping, to the lateral broadening due to multiple scattering, and to the effect of zero-point motion on the Coulomb image of a molecule.

The results of this work have been published.¹

*Argonne Fellow from Odense University, Odense, Denmark.
VIII. ATOMIC PHYSICS AT ATLAS AND THE ECR SOURCE

The narrow energy spread of beams from ATLAS together with the continuous energy variability and the capability of operation in a deceleration mode make it an ideal machine for the study of the atomic physics of highly-ionized atoms. The Uranium Upgrade of ATLAS will provide more intense beams and an increased range of ion species and further increase the usefulness of ATLAS for atomic-physics studies. The Uranium Upgrade has been delayed while some technical effort was devoted to improving the safety systems at ATLAS, but the final phase of the upgrade will be completed by the summer of 1992.

A number of outside groups have been attracted to the opportunities offered by ATLAS. Atomic structure studies are being pursued in collaboration with a group from Notre Dame University, a group from Bochum, Germany, and a group from NIST. The University of Toledo, Texas A&M University, and the Weizmann Institute have also been involved in atomic-structure experiments at ATLAS. Atomic-collision studies are carried out in collaboration with physicists from Lawrence Livermore, Western Michigan University, and LBL.

Atomic-physics experiments at ATLAS have produced some of the most precise determinations of lifetimes of few-electron ions in high-Z systems. Such measurements are sensitive to higher-order relativistic corrections to the calculations which depend strongly on Z. Other atomic-physics programs at ATLAS are aimed at precision spectroscopy of highly-charged few-electron ions. Precise measurements of transition energies test relativistic and radiative corrections to the energy-level calculations as well as correlation effects in the simplest systems where such effects are present. The program, in collaboration with Notre Dame, utilizes ultraviolet spectroscopy to study transitions within the n = 2 shell of two- and three-electron ions. Our work with the NIST group involves using X-ray spectroscopy to study transitions in one- and two-electron ions. We are working with E. Tröbert of Bochum to study intercombination transitions in highly-charged Mg-like, Al-like and Si-like ions. The ion-atom collision work at ATLAS has concentrated on the study of dielectronic recombination of channelled ions.

The ECR ion source, part of the ATLAS upgrade, provides beams of slow, highly-charged ions which are also ideal for atomic physics measurements. For this reason, two atomic-physics beamlines have been set up at the source. This facility is unique because the ECR ion source is on a high-voltage platform and ion energies from a few keV to about 300 Q keV are available (Q is the extracted charge state). All other existing ECR ion sources used for atomic physics are limited to beam energies of less than about 20 Q keV.

A laser lab which has been set up next to one of the atomic-physics beamlines is an important component of the experimental program at the ECR ion source. One of the projects, utilizing this lab, involves the study of electron capture in a sodium target which has been polarized by laser optical pumping. The goal of this work is to develop a general method for polarizing highly-charged ions. Another experimental program uses the technique of collinear laser spectroscopy to make precision measurements of transition energies in the n = 2 levels of He-like ions.
a. Lifetime of the $2^1S_0$ Level in Helium-Like Br (R. W. Dunford, S. Cheng, E. Kanter, H. G. Berry, L. J. Curtis,*, and A. E. Livingston†)

The $2^1S_0$ level in helium-like ions is forbidden to decay to the ground state by single-photon emission due to the angular-momentum selection rule. This state decays by the emission of two photons. Drake¹ has calculated the transition probability for two-photon decay of helium-like ions and included consideration of relativistic effects for the first time. In an earlier ATLAS experiment,² we measured the lifetime of the $2^1S_0$ level in helium-like nickel to about 1%. This experiment provided confirmation of the theoretical lifetime and sensitivity to the relativistic corrections which are about 3% in nickel. In order to provide a more stringent test, we recently completed a measurement in helium-like Br, where the relativistic corrections are larger.

In the experiment, a beam of bromine ions prepared in the 33+ charge state was incident on a thin carbon target which excited some of the ions to the $2^1S_0$ level. The decay radiation coming from the beam after passing through the carbon target (12 μg/cm²) is observed with three Si(Li) detectors. The two-photon coincidence rate was measured as a function of foil-detector distance in order to determine the lifetime. A fourth lower-resolution x-ray detector moves with the target for normalization. The requirement of a coincidence with the sum of the energies in the two detectors equalling the $2^1S_0-1^1S_0$ transition energy provides a powerful signature to select the helium-like two-photon decay mode. This gives a strong suppression of transitions from two-photon decay of hydrogen-like bromine and from background.

Although the data analysis for this experiment is still in progress, the data are excellent and it appears that the final result will be better than our goal of 1%. This experiment provides the best test to date of the relativistic corrections to the two-photon decay rate in any system.

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†University of Notre Dame, Notre Dame, IN.
In order to test theoretical calculations of transition energies in two- and three-electron ions, we have obtained high-precision spectra at ATLAS using a crystal x-ray spectrometer developed at NIST. The spectrometer observes x-rays formed after electron capture in a gas target (Fig. VIII-1). An important aspect of this work is the use of the accel/decel technique\(^1\) in which ions are accelerated, stripped to one-electron, then slowed down and delivered to a gas target where they pick up electrons under single-collision conditions. The deceleration is required in order to obtain adequate cross sections for electron pickup in the gas target. The importance of using a gas target is that single-electron pickup is highly favored and clean, symmetrical spectral lines, uncontaminated by lines from multielectron pickup, are obtained.

Data analysis is in progress for a preliminary measurement of the 2p-2s transition energy in helium-like Ca\(^{18+}\). In this measurement, hydrogen-like Ca ions were incident on an argon gas target and the x-rays emitted after electron capture were analyzed with the spectrometer. In the same ATLAS run we took data with an incident helium-like Ca beam and observed doubly-excited Li-like ions formed by simultaneous electron excitation and electron pick-up in an ion-atom collision. The latter results allow precision comparisons of experimental and theoretical transition energies and insight into collision mechanisms involving simultaneous electron pick-up and excitation.

\(^*\)Graduate Student, University of Illinois, Chicago, IL.
\(^\dagger\)National Institute of Standards and Technology, Gaithersburg, MD.

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**CALCIUM X-RAY SPECTRUM**

Fig. VIII-1. Calcium X-ray spectrum with He-like beam incident on target. Solid lines are fits to He-like and lithium-like lines.
At intermediate and high nuclear charge, measurements of the 2s-2p transition energies provide sensitive tests of many-body relativistic and QED calculations. We are investigating these transition energies at intermediate $Z$ where the experiments are most sensitive to relativistic correlations since non-relativistic effects are minimized and transition energies are not dominated by the one-electron Lamb shift.

The current goal of this work is to make a measurement of the $1s2s\,^3S_1-1s2p\,^3P_0$ transition energy in helium-like nickel. This measurement coupled with our earlier measurement\(^1\) of the $1s2s\,^3S_1-1s2p\,^3P_2$ transition in helium-like nickel will enable us to obtain a result for the $J = 0$ to $J = 2$ fine structure of the $^3P$ state. At present, there are no accurate measurements of the $J = 0$ member of this multiplet above $Z = 17$. The most accurate calculations\(^2\) of the helium-like spectra made by Gordon Drake consist of non-relativistic variational calculations, with relativistic corrections added perturbatively. There is a systematic discrepancy between these calculations and the best experimental data for the $J = 0$ transition, with nearly all measured transition energies being less than the theoretical values. This discrepancy may be due to contributions of higher order in $Z$. This could be clarified by measurements at higher $Z$.

The longer lifetime and lower intensity of the $1s2s\,^3S_1-1s2p\,^3P_0$ transition makes this component difficult to measure and so a number of improvements are needed to increase our sensitivity. One of the improvements has been the development of position-sensitive detectors for the monochromators. By replacing the exit slits and channeltron with microchannel-plate detectors and position-sensitive anodes, we have greatly increased the detection efficiency of the system. In an ATLAS run in July 1991, a position-sensitive detector was tested with our grazing-incidence monochromator and it worked well. Also in that run we were able to reduce the background in the spectrum by suppressing ion beam related signals. This was achieved by shielding the beam dump and by timing the arrival of detector pulses relative to a beam rf. The rf timing technique worked particularly well. Most of the background was uncorrelated with the "prompt" photon signals coming from excited atomic levels. By cutting out all events which do not come at the proper time relative to the beam, the background was greatly reduced (see Fig. VIII-2).


When fast heavy ions are channeled between the ordered rows of a crystal lattice, small-impact-parameter collisions with target atoms are reduced considerably. Hyperchanneled ions (ions whose low transverse momenta cause their motions to be limited to a single axial channel) exhibit an anomalously high probability for maintaining their initial charge state in moving through crystals many times thicker than amorphous targets of equilibrium thickness. These "frozen" charge states represent that fraction of the beam which is hyperchanneled and thus avoid close collisions with the target atoms. Hence, for compact channeled ions, only large-impact-parameter processes are possible. Previously, we had conducted two experiments exploiting the narrow energy resolution of ATLAS and using the phenomenon of frozen charge states to study dielectronic recombination (DR). In the DR process, single-electron capture is accompanied by simultaneous (correlated) projectile excitation via the electron-electron interaction. This process is the inverse of the Auger effect and is highly dependent upon electronic correlations in the intermediate

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excited state. Accurate measurements of state-selective DR cross sections can thus provide stringent tests of atomic structure calculations in heavy few-electron systems. Reliable absolute cross section measurements for dielectronic recombination of heavy few-electron ions with cold electrons have heretofore been impractical.

In our first experiment,\(^1\) we carried out high-resolution measurements of the energy loss and corresponding charge-changing probabilities of 267-320 MeV Ti\(^{19+}\) and Ti\(^{20+}\) ions channeled along the <110> axis of a thin (400 Å) gold crystal. By separating the hyperchanneled particles through their energy loss (with the area III spectrograph), we found that the best-channeled ions demonstrated dramatically enhanced probabilities for electron capture in the region of projectile velocity corresponding to the capture of free electrons. The widths of the observed resonances were much narrower than observed in similar measurements with Si crystals, and nearly an order of magnitude narrower than expectations based on a free electron model of the crystal.

To test these results, we attempted to duplicate those measurements with much finer energy steps than were used in the earlier measurements. The experiments were again carried out with 264-324 MeV Ti\(^{19+}\) and Ti\(^{20+}\) ions channeled along the <110> axis of a thin gold crystal. The gold crystal, supplied by J. Chevalier of Aarhus University, was somewhat thicker (1200 Å) and also exhibited microscopic pinhole structure. Preliminary results show no evidence for resonance structure with the Li-like beam and only weak evidence with the He-like beam. The results are further clouded by the poor frozen charge state fraction (68\%) which was obtained in this measurement compared to the nearly 90\% fraction observed with the thinner crystal. Because of these problems with the crystal, it appears that the ultimate results of the data analysis will remain inconclusive.

In a further effort to confirm these results, we have also collaborated in an experiment at Chalk River Nuclear Laboratory utilizing 18-MeV/amu He-like Br ions channeled in a thick Si crystal. In this experiment, the crystal quality was exceedingly good, giving a frozen charge fraction in excess of 98\%. Data analysis is still in progress.

IX. ATOMIC PHYSICS AT SYNCHROTRON LIGHT SOURCES

A research program in atomic, molecular and optical physics with x-rays has been initiated to complement the program of accelerator-based atomic physics research within the Division. This new direction for the Division's research is justified by a consideration of the fundamental characteristics of x-rays and their interaction with matter, and the advantages these characteristics bring to experimental investigations. The development of an x-ray-based research program in the traditional areas of atomic physics is expected to parallel the historical developments in atomic physics with longer-wavelength (near-visible) radiation. A healthy synergy is expected between atomic physics research and molecular and optical physics research.

In previous years the Division's research activities in atomic physics with synchrotron radiation were conducted through collaboration with on-going research programs based primarily at other institutions. With the addition of two staff members, both of whom have extensive experience in synchrotron-radiation research, the group's activities are now capable of fully independent operation. One of them provides the further benefit that the group has assumed partnership with the Quantum Metrology Division of NIST as part of the Participating Research Team for NSLS beamline X-24A. This agreement will provide the group with priority access to this state-of-the-art dedicated facility for research in AMO physics with synchrotron radiation.

The group's activities are currently supported by the Laboratory Director's Research Development funds. A proposal for major funding for this project has been submitted to DOE and is currently under consideration.

This research program is expected to benefit enormously from the construction of a third-generation synchrotron-radiation facility, the Advanced Photon Source (APS), at Argonne over the next few years. The Physics Division is a participant in the proposed Basic Energy Sciences Synchrotron-Radiation Center (BESSRC) which is to be located at the APS. This center will include a dedicated experimental station for our research in AMO physics, and will provide the group with access to an x-ray source with unprecedented brightness. The BESSRC has been accepted by the APS as one of eight Collaborative Access Teams (CATs) to have unconditional approval to proceed with plans for construction. A proposal for construction and operating funds for the BESSRC has been submitted to DOE and is now being considered.
a. **Photoionization of Multi-Charged Stored Ions at the National Synchrotron Light Source** (Y. Azuma, E. G. Berry, N. Berrah-Mansour,* S. D. Kravis,† D. A. Church,† M. Druetta,‡ B. Johnson,§ K. Jones,§ J. Levin,¶ T. M. Meron,§ and I. A. Selli§)

The photoionization experiments of stored multi-charged ions with synchrotron x-rays by this collaboration were completed in 1990. The experiments took place at the Brookhaven National Synchrotron Light Source (NSLS) X-26C beamline utilizing a modified Penning-type ion trap with two slots in the ring electrode to permit passage of the photon beam.

Focused white synchrotron radiation between 3 keV and 15 keV was used to accomplish K-shell photoionization of stored multi-charged argon ions. The distribution of photo-ion charge states resulting from vacancy cascades and electron shakeoff following K-shell photoionization of Ar$^{2+}$ ions was measured. These measurements were made as a function of the background gas pressure. Time-reversed integration of coupled differential equations was used to account for contributions from electron capture by the residual gas. The results are in reasonable agreement with simple theoretical predictions.

A short summary of the results was published and a further publication completes this work.¹ We do not anticipate further significant ion-trap work using synchrotron radiation until the APS comes on line.

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Double photoionization of helium has been studied extensively at photon energies from near threshold (79 eV) up to about 200 eV, principally to test correlation effects in single- and multiple-ionization calculations. Most theories predict that this ratio approaches asymptotically to a constant value at high energy. We undertook to measure this asymptotic ratio at a photon energy of 2.8 keV.

The apparatus is a crossed-beam geometry, with a helium jet that is oriented perpendicular to both the NSLS photon beam and a time-of-flight (TOF) analyzer for photo-ion charge-state analysis. We achieved the first measurement of the ratio of double-to-single photoionization well above threshold, and obtained a value for the ratio \( \text{He}^{++}/\text{He}^+ = 1.6\% \pm 0.3\% \) at 2.8 keV (see Fig. IX-1). This value is much lower than found in the results of recent many-body perturbation-theory calculations of Hino and Ishihara (3.8%) and of Amusia (2.3%). A semi-empirical calculation by Sampson predicts 1.2%, but with no asymptotic value for the ratio (his ratio shows a decrease at higher photon energies).

Further measurements are in progress at both higher and lower photon energies.

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Fig. IX-1. Time-of-flight spectrum of \( \text{He}^{++} \) and \( \text{He}^+ \).
c. **Time-of-Flight (TOF) Ion Spectroscopy** (T. LeBrun, N. Berrah-Mansour,*
H. G. Berry, D. S. Gemmell, P. L. Cowan, Y. Azuma, J. Levin,†
I. A. Sellin,‡ R. Miller,‡ and N. Keller‡)

A TOF ion spectrometer and an electron detector were built at Argonne and
operated at NSLS beamline X-24A. Initial measurements of the ion charge-state
distribution and of the excitation-energy dependence of the production of
several charge states were performed for argon gas in the vicinity of known
multi-electron excitation thresholds. TOF ion spectroscopy is expected to be
extended to studies of open-shell atoms produced either by molecular
dissociation or as metal vapor.

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d. **Inner-Shell Multiple-Photoexcitation Studies via X-ray Absorption**
Spectroscopy (XAS) (Y. Azuma, P. L. Cowan, A. Kodre,*
S. J. Schaphorst,† B. Crasemann,‡ M. H. Chen,§ G. S. Brown,¶
T. Åberg,§ and J. Tuikkki§)

A collaborative series of experiments on inner-shell double photoexcitations
was initiated in 1990. The goal has been the study of dynamic correlation
effects for inner-shell electrons where strong relativistic perturbations can
be observed. The initial experiment took place in April 1990, at the Stanford
Synchrotron Radiation Laboratory (SSRL) SPEAR storage ring. Absorption
spectroscopy measurements were performed at a bending-magnet beam line,
equipped with a silicon (220) double-crystal monochromator. Single-photon two-
electron excitation structures of Kr and Xe were measured. In particular,
double s-shell features were sought for possible Breit interaction effect in
the $1s_0 - 3s_1$ splitting which has not been observed previously. Work on the
analysis continued in 1991 with parallel theoretical efforts involving the
Helsinki University of Technology. The following conclusions were drawn,
comparing the experimental results with Hartree-Fock and Dirac-Fock
calculations including frequency-dependent Breit interaction and quantum-
electrodynamic contributions.

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†University of Central Florida, Orlando, FL.
‡University of Oregon, Eugene, OR.
§Lawrence Livermore National Laboratory, Livermore, CA.
¶Stanford Synchrotron Radiation Laboratory, Stanford, CA.
#Helsinki University of Technology, Helsinki, Finland.
1) The Kr (1s,4p) edge position was in agreement with theory, but the magnitude of bound-bound excitations were found to differ substantially.

2) For the Kr (1s,3d) and (1s,3p) edge, qualitative agreement between experiment and theory were found except near thresholds.

3) The Kr (1s,2s) edge, pursued for the measurement of the 3S - 1S splitting, was inconclusive and requires much further effort.

Experimental work will continue with improved absorption cells and detection schemes. Also, related efforts to study the Breit interaction effects through measurements of hypersatellites in X-ray fluorescence following double-K photoionization will be pursued.

e. **Coincidence Studies of Recoil Ions and Auger Electrons** (Y. Azuma, N. Berrah-Mansour,* J. C. Levin,† I. A. Sellin,† C. Biedermann,† N. Keller,† and D. Lindle†)

Inner-shell near-threshold photoionization studies employing the photo-ion Auger electron coincidence experiments have been pursued in collaboration with a group at Oak Ridge National Laboratory. The strong photon energy dependence of the photo-ion charge-state distribution following inner-shell excitation near threshold is a remarkable manifestation of dynamic electron-electron correlation effects. In order to obtain a meaningful interpretation of the photo-ion charge-state distribution, it is essential to resolve and disentangle the process for each individual Auger decay channel. This has been achieved by measuring the photo-ion charge states in coincidence with each particular Auger electron. The apparatus employs a cylindrical mirror analyzer (CMA) for electron detection and a time-of-flight (TOF) analyzer for photo-ion charge-state analysis (see Fig. IX-2).

![Fig. IX-2. Schematic diagram of the electron-ion coincidence studies setup.](image-url)
A preliminary attempt on the K-shell photoionization of krypton was made in May 1990, at Cornell High Energy Synchrotron Source (CHESS). The feasibility of these measurements was demonstrated and follow-up runs are being planned.

Further coincidence studies of time-of-flight ions and energy-analyzed electrons have continued at the Brookhaven National Synchrotron Light Source on the X-24A beam line.

K-shell photoionization of neon was attempted at the NSLS X-24A beam line. Some preliminary data on total charge distribution were obtained but no coincidence measurement could be done due to the very low efficiency of the multilayer monochromator near the 900-eV region. Also, measurements on the double photoionization of He in this photon-energy region were attempted without success. Further work in this photon-energy region will require improvement in the monochromator performance.

The measurements of Ar charge distributions coincident with K-L23L23, K-L1L23 and the K-LM Auger electrons following near-threshold photoionization were accomplished. The photon energy resolution employed for this measurement was higher than in the results reported previously. The resolution obtained from the X-24A beam line at NSLS, utilizing a germanium double-crystal monochromator, was sufficient to resolve structure in Ar$^{3+}$ due to resonant excitation of the K electron to the np levels and its subsequent shake off. Substantial Ar$^{3+}$ persists above the K-ionization threshold resulting from recapture of the K photoelectron through post-collision interaction. Double Auger processes have also been revealed. Further analysis is in progress.

Plans for future experiments include studies on open-shell elements such as Cl, Br and I. Atomic targets of such elements will be produced by RF discharge and/or by photodissociation of the mother molecule by lasers.

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X-ray resonant Raman scattering has great promise as a high-resolution x-ray probe of the electronic structure of matter. Unlike XAS and conventional XES, XRRS is not restricted in energy resolution by inner-shell-hole-lifetime broadening. Furthermore, measurements of polarization and angular anisotropic effect have potential value for studies of both symmetries of electronic states and atomic structure of molecules.

One area of emphasis has been in establishing a detailed understanding of the XRRS of atomic argon. A semi-empirical theoretical model has been developed and refined to achieve excellent agreement with extensive data collected at beamline X-24A. Additional observations of XRRS from multi-vacancy excitations in argon gas have also received attention.

Studies of XRRS from molecular gases have proved to be extremely illuminating regarding the effects of polarization and angular anisotropy of the x-ray resonant Raman effect. The value of studies of molecules stems partially from the ready availability of polarizing x-ray spectrometer crystals for chlorine and sulfur K emission in the form of Si(111) and InSb(111), respectively. Studies of XRRS from Cl- and S-containing molecules have also permitted observations for molecules with significantly different symmetries. Results for atoms in molecules with linear (such as methyl chloride) and non-linear (hydrogen sulfide) bonding symmetries were published in 1991. In addition analysis of results for the symmetric case of molecular chlorine gas and the cubicly-symmetric case of sulfur hexafluoride received much attention. These studies of molecules have also led to the discovery of polarization and angular anisotropy of core-to-core transitions, indicating significant inter-shell correlation effects. These latter observations have been observed in the case of atomic argon gas as well.

Previous measurements of polarized XRRS at the K-edges of argon and various molecular gases and in crystals of KCl will be complemented by measurements of the effective L-edges of various elements including xenon gas.

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Extensive measurements of multi-vacancy x-ray emission satellites have been performed for argon gas and other samples as a continuation of the pioneering work of Deslattes et al. These studies are directly complementary to the x-ray absorption spectroscopic (XAS) studies of multiple excitations mentioned above.

Especially intriguing is preliminary evidence of the argon K-α hypersatellite obtained in collaboration with the University of Oregon group. Measurement of the hypersatellite spectrum is expected to test directly calculations of relativistic retardation effects on electron-electron correlation.

Another new direction for these studies is the observation of the radiative Auger effect. Previous studies of correlation effects have concentrated on the case where a single excitation x-ray excites multiple electrons. The radiative Auger effect is due to multiple electron transitions during the emission of a single x-ray photon.

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The atomic physics group is involved in experiments at three Physics Division accelerator facilities -- the ATLAS accelerator, BLASE (Beam-Laser), and the Dynamitron. The last two accelerators, BLASE and the Dynamitron, are dedicated solely to our atomic physics program.

One beamline at ATLAS is set up for atomic physics experiments, which occur on a periodic basis as determined from the ATLAS User schedule. In addition, synchrotron-based experiments take place at the National Synchrotron Light Source (NSLS) X-24A beamline. A member of our group is responsible for this beamline under the terms of an agreement with NIST.

A technical support group is available for assisting with atomic physics experiments on these accelerators and for other experiments. The staff of this group includes a Mechanical Engineer who is in charge of design, technical improvements, and the setup of experimental beam lines; two operators of the Dynamitron who also work on technical projects at each of the other accelerators; a Scientific Associate whose primary responsibility is BLASE and the synchrotron-based program, and helping with maintenance and technical design at the other facilities. Two of these people are also responsible for helping individual experimental groups.

The technical support group was largely responsible for implementing many new safety and environmental procedures for operation of all the Physics Division accelerators. Documentation for the procedures was also rewritten and brought up-to-date.


The atomic physics beam line set up at the ATLAS heavy-ion accelerator is used for a variety of experiments. The beam line has two focussing regions separated by ten meters. In the first region, an experimental setup used to study forbidden transitions consists of a chamber containing an array of four silicon x-ray detectors and a movable foil target. An optical encoder on the target translation stage precisely determines the position of the foil target. This apparatus has been used for studies of hyperfine quenching of forbidden decays. A target chamber located at the second focus on the beam line is used with a grazing-incidence monochromator for precision spectroscopy of highly-charged few-electron ions.

The split-pole magnetic spectrograph has also been used by the atomic physics group to study ion-atom collisions. The target chamber and detectors required for these experiments are installed immediately before the runs and removed afterwards.

Atomic technical personnel are not generally involved in development of the APEX (ATLAS Positron Experiment) system.

The ECR ion source which was built as part of the Uranium Upgrade of ATLAS is also used directly for atomic physics experiments. Many of the experiments take advantage of the high-voltage platform which provides beam energies up to 300 kV times the charge state of the extracted ions.

A switching magnet installed in the ATLAS positive-injection line is used to direct the beam from the ECR source into either of two atomic-physics beam lines. The first beam line consists of focusing elements, steerers, slits, and diagnostic elements which prepare the beam for the experimental section. The experimental section consists of two target chambers. The first chamber is used for ultraviolet spectroscopy. Either gas or foil targets are viewed by a 1-m normal-incidence monochromator and a 2.2-m grazing-incidence monochromator. The second element in the beam line is a scattering chamber which is used for electron spectroscopy. The second beam line contains one experimental section which is adjacent to a dye-laser facility. This beam line is used for laser/ion-beam interaction studies and polarization studies using a sodium-jet target which can be polarized by laser optical pumping.

*Kansas State University, Manhattan, KS.

The BLASE Facility (L. Young and C. A. Kurtz)

BLASE is a facility designed for resonant interactions between a positive-ion beam and a laser. An ion source resides on a highly stabilized 150-kV platform; a mass analyzer is provided by a 90° magnet. Resonant radiofrequency (rf) transitions are induced by a specially designed rf interaction region. Primary use of the facility is dedicated to high-precision spectroscopic experiments.

Several spectroscopic experiments were performed at this facility during the past fiscal year.

Substantial efforts have been directed toward complying with electrical, optical, and other safety standards.

The Dynamitron is a high-current stabilized 5-MV accelerator that can provide singly-charged beams of most atomic ions and many molecular ions. During this past year, the accelerator has been used only by the atomic physics program for work with fast molecular ions.

We have installed in the Dynamitron high-voltage terminal a supersonic expansion source of vibrationally cold molecular ions. This source, which consists of a pulsed-jet supersonic gas expansion crossed by a beam of ionizing electrons, presented a major technological challenge because of the requirements of pumping background gas from the high-voltage terminal in order to achieve the high stagnation pressures necessary for vibrational cooling. This source has demonstrated substantial cooling of several molecular ions and we are able to obtain experimental beams of such molecular ions with nearly pure ground-state populations.

Overall, the Dynamitron continued to perform well during the past year. It was scheduled to run experiments for 7 weeks throughout the year. When the machine was not being used for experiments, the technical staff assisted in the construction of beam lines, small accelerators, ion sources and accomplished machine modifications, repairs, and safety improvements.
STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the staff of the Physics Division for the year ending March 31, 1992. The program heading indicates only the individual's current primary activity.

EXPERIMENTAL NUCLEAR PHYSICS

Regular Experimental Staff Members

Irshad Ahmad, Ph.D., University of California, 1966
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
†Michael P. Carpenter, Ph.D., Niels Bohr Institute, 1988
Cary N. Davids, Ph.D., California Institute of Technology, 1967
‡Stuart J. Freedman, Ph.D., University of California, 1972
Donald F. Geesaman, Ph.D., State University of N.Y., Stony Brook, 1976
§Bruce G. Glagola, Ph.D., University of Maryland, 1978
¶Walter F. Henning, Ph.D., Technical University of Munich, 1968
Roy J. Holt, Ph.D., Yale University, 1972
Harold E. Jackson, Jr., Ph.D., Cornell University, 1959
Robert V.F. Janssens, Ph.D. Univ. Catholique de Louvain, Belgium, 1978
Sheldon B. Kaufman, Ph.D., University of Chicago, 1953
Teng Lek Khoo, Ph.D., McMaster University, 1972
Walter Kutschera, Ph.D., University of Graz, Austria, 1965
Richard C. Pardo, Ph.D., University of Texas, 1976
Karl Ernst Rehm, Ph.D., Technical University, Munich, 1973
**John P. Schiffer, Ph.D., Yale University, 1954
Kenneth W. Shepard, Ph.D., Stanford University, 1970
Benjamin Zeidman, Ph.D., Washington University, 1957

*In charge of ATLAS operations and accelerator development.
†Postdoctoral Appointee until July 1, 1991.
‡Joint appointment with the University of Chicago. On leave at the University of California, Berkeley until October 1, 1992.
§ATLAS User Program Administrator.
¶Director of the Physics Division as of November 18, 1991.
||ATLAS Operations Manager.
**Associate Director of the Physics Division. Joint appointment with the University of Chicago.
Other Experimental Staff Members

*Melvin S. Freedman, Ph.D., University of Chicago, 1942
†Thomas Happ, Ph.D., University of Frankfurt, W. Germany, 1989
†Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937
†Frank J. Lynch, B.S., University of Chicago, 1944
§David H. Poterveld, Ph.D., Caltech, 1988
†G. Roy Ringo, Ph.D., University of Chicago, 1940
†George E. Thomas, B.A., Illinois Wesleyan, 1943
†Jan L. Yntema, Ph.D., Free University of Amsterdam, 1952

THEORETICAL NUCLEAR PHYSICS

Regular Theoretical Physics Staff Members

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
§Stephen Landowne, Ph.D., Carnegie-Mellon University, 1970
Tsung-Shung Harry Lee, Ph.D., University of Pittsburgh, 1973
Steven C. Pieper, Ph.D., University of Illinois, 1970
†Craig T. Roberts, Ph.D., University of Melbourne, 1989
Robert B. Wiringa, Ph.D., University of Illinois, 1978

Other Theoretical Nuclear Physics Staff

**Arnold R. Bodmer, Ph.D., Manchester University, 1953
*Dieter Kurath, Ph.D., University of Chicago, 1951
*Harry J. Lipkin, Ph.D., Princeton University, 1950
*James E. Monahan, Ph.D., St. Louis University, 1951
††Vijay Pandharipande, Ph.D., University of Bombay, 1969
††Murray Peshkin, Ph.D., Cornell University, 1951

*Resident Associate Guest Appointee.
†Term appointment.
§Term appointment. Postdoctoral appointee until October 1, 1991.
‖On assignment at the National Science Foundation until June 1992.
**Resident Associate Guest Appointee from the University of Illinois at Chicago.
††Special Term Appointee from the University of Illinois at Urbana.
Regular Atomic and Molecular Physics Staff Members

Yoshiro Azuma, Ph.D., University of Oregon, 1985
H. Gordon Berry, Ph.D., University of Wisconsin, 1967
Paul L. Cowan, Ph.D., Pennsylvania State University, 1977
Robert Dunford, Ph.D., University of Michigan, 1978
*Donald S. Gemmell, Ph.D., Australian National University, 1960
Elliot P. Kanter, Ph.D., Rutgers University, 1977
†Zeev Vager, Ph.D. Weizmann Institute of Science, 1962
Linda Young, Ph.D., University of California, Berkeley, 1981

Other Atomic and Molecular Physics Staff

†R. Stephen Berry, Ph.D., Harvard University, 1956
§William J. Childs, Ph.D., University of Michigan, 1956
¶Nora Mansour, Ph.D., University of Virginia, 1987
||F. Paul Mooring, Ph.D., University of Wisconsin, 1951
|||Gilbert J. Perlow, Ph.D., University of Chicago, 1940

*Director of the Physics Division until November 18, 1991.
†Joint Appointment with Weizmann Institute of Science, Rehovot, Israel.
†Special Term Appointee from the University of Chicago.
§Special Term Appointee.
¶Guest Faculty Research Participant as of October 18, 1991.
||Resident Associate Guest Appointee.
TECHNICAL AND ENGINEERING STAFF
(and areas of activity)

Peter J. Billquist. ECR heavy-ion source.
John P. Greene (M.S. DePaul University, 1982). Target preparation.
Dale J. Henderson (B.S. Elmhurst College, 1951). Detector development.
Raymond B. Kickert. Experimental equipment maintenance.
Paul Markovich (B.S. Purdue University, 1972). Surface chemistry, ATLAS upgrade.
Philip Strickhorn (B.S. DeVry, 1990). Technical assistance at ATLAS.
Gregory Wiemerslage (B.S. Elmhurst College, 1990). Technical assistance at ATLAS.

*Joined the Physics Division on June 17, 1991.
ADMINISTRATIVE STAFF

*Allan Bernstein, M.B.A., Rosary College, 1986
   James E. Nelson, B.A., University of Illinois, 1975

TEMPORARY APPOINTMENTS

POSTDOCTORAL APPOINTEES

†Michael Carpenter (from Niels Bohr Institute, Roskilde, Denmark):
   Heavy-ion research at ATLAS.
   (February 1989--July 1, 1991)

Song Cheng (from Kansas State University, Manhattan, Kansas):
   Atomic physics at ATLAS.
   (August 1991-- )

Kevin Coulter (from Princeton University, Princeton, New Jersey):
   Medium-energy physics.
   (December 1988-- )

Patricia B. Fernandez (from Univ. of Washington, Seattle, Washington):
   Heavy-ion research at ATLAS.
   (January 1989--May 1991)

Martin Freer (from Birmingham University, Birmingham, UK):
   Heavy-ion research at ATLAS.
   (April 1991-- )

Brian K. Fujikawa (from Calif. Inst. of Technology, Pasadena, California):
   Weak interactions studies.
   (October 1989--November 1991)

Richard Harkewicz (from Michigan State University, E. Lansing, Michigan):
   Accelerator development and research at ATLAS.
   (March 1992-- )

Roland Henry (from Rutgers University, New Brunswick, New Jersey):
   Heavy-ion research at ATLAS.
   (January 1992-- )

†Edward R. Kinney (from Mass. Inst. of Technology, Cambridge, Mass.):
   Medium-energy research.
   (June 1988--August 1991)

   Daniel Krakauer (from University of Maryland, College Park, Maryland):
   Weak interaction studies.
   (January 1989--June 1991)

*Assistant Director of the Physics Division.
†Promoted to regular staff on July 1, 1991.
†Resident Associate Guest Appointee as of August 12, 1991.
Torben Lauritsen (from SUNY, Stony Brook, NY):
Nuclear physics research at ATLAS.
(June 1990-- )

Thomas LeBrun (from University of Paris, France):
Atomic physics using synchrotron light sources.
(November 1991-- )

Yun Liang (from SUNY, Stony Brook, New York):
Heavy-ion research at ATLAS.
(August 1991-- )

Vassilios Papavassiliou (from Yale University, New Haven, Connecticut):
Medium-energy physics research.
(May 1991-- )

*David H. Potterveld (from Calif. Inst. of Technology, Pasadena, Cal.):
Medium-energy physics research.
(July 1988--October 1, 1991)

Bernard Matthew Poelker (from Northwestern University, Evanston Illinois):
Medium-energy physics research.
(January 1992-- )

Fernando Scarlassara (from INFN, Padova, Italy):
Heavy-ion research at ATLAS.
(December 1989--March 1991)

†Rocco Schiavilla (from University of Illinois, Urbana, IL):
Nuclear theory studies.
(May 1990-- )

†Alan H. Wuosmaa (from University of Pennsylvania, Philadelphia, Pa):
Heavy-ion research at ATLAS.
(September 1989-- )

Daniel Zajfman (from Technion, Haifa, Israel):
Coulomb-explosion studies.
(August 1989--September 1991)

Amina Zghiche (from C.E.N., Saclay, France):
Medium-energy research.
(January 1990--October 1991)

*Regular staff term appointment as of October 1, 1991.
†Enrico Fermi Scholar.
Long-Term Visitors (at Argonne more than 4 months)

Nemitala Added (University of Sao Paulo, Brazil):
ATLAS development.
(April 1991--
)

Allan M. Baxter (Australian Nat. Univ., Canberra, Australia):
Heavy-ion research at ATLAS.
(July 1990--May 1991)

Dan Berkovits (Hebrew University, Jerusalem, Israel):
Nuclear astrophysics research at ATLAS.
(February 1992--
)

Marcello D. Farraretto (University of Sao Paulo, Brazil):
ATLAS development.
(October 1990--
)

Yuichiro Nagame (JAERI, Tokyo, Japan):
Work on FMA project at ATLAS.
(July 1990--September 1991)

Prakash Potukuchi (Nuclear Science Center, New Delhi, India):
ATLAS development.
(October 1991--
)

Amit Roy (Nuclear Science Center, New Delhi, India):
ATLAS development.
(October 1991--
)

*Peter Sigmund (Odense University, Odense, Denmark):
Particle penetration phenomena.
(January 1992)

Francesca Soramel (University of Padova, Italy):
Heavy-ion research at ATLAS.
(September 1991--
)

Dmitri Toporkov (Institute for Nuclear Physics, Novosibirsk, UR):
Medium-energy physics research.
(February 1992--
)

Resident Graduate Students

Ian Bearden (Purdue University, W. Lafayette, Indiana):
Heavy-ion research at ATLAS.
(January 1990-- )

Kanwarjit S. Bindra (Vanderbilt University):
FMA development at ATLAS.
(May 1990-- )

John C. Gehring (University of Chicago, Chicago, Illinois):
Heavy-ion research at ATLAS.
(June 1990-- )

Timothy J. Graber (University of Illinois, Chicago, Illinois):
Coulomb-explosion studies.
(October 1989-- )

Nicholas Kaloskamis (Yale University, New Haven, Connecticut):
APEX experiment at ATLAS.
(November 1991-- )

Mark L. Raphaelian (University of Illinois at Chicago, Illinois):
Accelerator-based atomic physics.
(January 1987--July 1991)

Jamal Suleiman (University of Illinois, Chicago, Illinois):
Atomic physics research.
(October 1991-- )

Mark Wolanski (University of Chicago, Chicago, Illinois):
Weak interaction studies.
(July 1991-- )

Danshao Ye (University of Notre Dame, Notre Dame, Indiana):
Heavy-ion research at ATLAS.
(February 1989--August 1991)

Short-Term Visitors  (at Argonne less than 4 months)

A. Faculty

Vladimir Dmitriev (Inst. Nuclear Physics, Novosibirsk, USSR):
Medium-energy physics collaboration.
(December 1991)

*Scott Fricke (University of Dallas, Texas):
Theoretical physics studies.
(June-July 1991)

*Faculty Research Participant.
*Edward L. Hohman (York Community High School, Elmhurst, Illinois):  
   Summer high-school student coordinator.  
   (June--August 1991)

†Dimitri F. Kusnesov (Michigan State University, E. Lansing, Michigan):  
   Theoretical physics studies.  
   (July 1991)

*Nora Mansour (Western Michigan University, Kalamazoo, Michigan):  
   Atomic physics at synchrotron light sources.  
   (October 1991--)

Michael Paul (Hebrew University, Jerusalem, Israel):  
   Heavy-ion research at ATLAS.  
   (October-December 1991)

†Akunuri Ramayya (Vanderbilt University, Nashville, Tennessee):  
   Heavy-ion research at ATLAS.  
   (February-May 1991)

Bernhard Schneck (University of Munich, Germany):  
   Heavy-ion research at ATLAS.  
   (October-December 1991)

Ralf-Wolfgang Schulze (University of Hannover, Germany):  
   Nuclear theory studies.  
   (January-March 1991)

Qamar Usmani (Aligarh University, Aligarh, India):  
   Nuclear theory studies.  
   (July-September 1991)

Daniel Zajfman (Weizmann Institute of Science, Rehovot, Israel):  
   Atomic physics research.  
   (January 1992)

*Guest Faculty Research Participant.  
†Faculty Research Participant.
B. Graduate Students

*Wonkyun Chung (University of Notre Dame):  
  FMA development at ATLAS.  
  (August 1991-- )

*Jeffrey Hangst (University of Chicago, Chicago, Illinois):  
  Ordered ion beams.  
  (November 1988--October 1991)

*Jian Li (University of Chicago, Chicago, Illinois):  
  Atomic physics research.  
  (July 1991-- )

*Zhengtian Lu (University of Chicago, Chicago, Illinois):  
  Weak interactions studies.  
  (November 1991-- )

Aloy Perera (University of Rochester, Rochester, New York):  
  APEX experiment at ATLAS.  
  (August 1991-- )

*Thih-Yuen Tung (Northwestern University, Evanston, Illinois):  
  Nuclear physics experiments.  
  (September 1987-- )

*Zhou Yu (Northwestern University, Evanston, Illinois):  
  Intermediate-energy physics.  
  (September 1987-- )

*Guest Graduate Student.
Undergraduate Students

Sharon Bell (Southern University)
Elizabeth Besenfelder (Washington and Lee University)
Kevin Beyer (Loyola University)
Mark Briggs (Dartmouth College)
Germeline L. Calagday (California State University)
Eric Chisholm (Milsaps College)
Frank Daffin (Florida State University)
Darlene Davis (Alabama A & M University)
Badi Ebrahimifard (University of Connecticut)
Eric Chisholm (Milsaps College)
Clay B. Holroyd (University of California)
Felicia I. Ingram (Alabama A & M University)
Jason A. Janesky (University of Arizona)
Justin L. Mortara (University of Chicago)
Arthur B. Phillips (Talladega College)
Monica J. Plisch (University of Illinois)
Gloria B. Ramos (Florida International University)
Dante Roa (Florida State University)
Brian Rutherford (College of St. Francis)
Won P. Sim (California State Polytechnic University)
David Sowinski (Lewis University)
Kenneth St. Amant (Oklahoma State University)
Jamal Suleiman (University of Illinois, Chicago)
Brian J. Tieman (North Central College)
Tabatha K. Wade (Talladega College)
Andrew G. Wig (North Park College)
Joshua N. Winn (Massachusetts Institute of Technology)
Dale T. Woodin (Western Michigan University)

Pre-College Program  (Just Graduated from High School)
(June-August 1991)

Niel P. Anderson (York Township High School)
Jonathan Arndt (Hinsdale South High School)
Shannon J. Clark (Oak Park-River Forest High School)
Jacqueline Esthappan (Oak Park-River Forest High School)
Chris E. Glenn (Joliet West High School)
Brian E. Jurczyk (Argo Community High School)
Joseph J. Liaw (Naperville Central High School)
Chadwick A. Trujillo (Oak Park-River Forest High School)
PUBLICATIONS FROM APRIL 1, 1991 THROUGH MARCH 31, 1992

Journal Articles and Book Chapters

Laser Cooling of a Stored Ion Beam to 1 mK
J. S. Hangst, M. Kristensen, J. S. Nielsen, O. Poulsen, J. P. Schiffer, and P. Shi

Neutron Transfer at Large Distances in the System $^{36}$S + $^{92}$Mo
A. Wuosmaa, K. E. Rehm, B. G. Glagola, T. Happ, W. Kutschera, and P. L. H. Wolfs

K X-Ray Yields Associated with the Superdeformed Band of $^{192}$Hg

Gamma Ray Multiplicity Distributions in $^{160}$ + $^{152}$Sm Fusion Near and Below the Coulomb Barrier

Rotational Bands with Identical Transition Energies in Actinide Nuclei
I. Ahmad, M. P. Carpenter, R. R. Chasman, R. V. F. Janssens, and T. L. Khoo

Decay History and Magnetic Moments at High Spin in $^{152}$Dy
M. Hass, N. Benczer-Koller, G. Kumbartzki, T. Lauritsen, T. L. Khoo, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, E. F. Moore, F. L. H. Wolfs, Ph. Benet, and K. Beard

Proton Induced Fission of $^{238}$U at Extreme Sub-BARRIER Energies
J. C. Gehring, B. B. Back, R. R. Betts, P. B. Fernandez, D. J. Henderson, and Y. Nagame

Rotational Bands in the Mass 100 Region

Superdeformed Bands in $^{189,190}$Hg
Search for Large Cluster Breakup of \(^{40}\text{Ca}\)

B. R. Fulton, S. J. Bennett, M. Freer, J. T. Murgatroyd, S. C. Allock,
W. D. Rae, A. E. Smith, R. R. Betts, B. Back, S. Sanders, and F. Videbaek

Half-life of \(^{41}\text{Ca}\)

M. Paul, I. Ahmad, and W. Kutschera

Energy Dependence of One- and Two-Particle Transfer Reactions in the System \(^{160}\text{O} + ^{90}\text{Zr}\)

K. E. Rehm, J. Gehring, B. Glagola, W. C. Ma, W. Phillips, F. L. H. Wolfs

Nuclear Charge Separation of Low-energy Medium-mass Ions with a Gas-filled Magnetic Spectrometer

F. Scarlassara, B. C. Glagola, W. Kutschera, K. E. Rehm, and A. H. Wuosmaa

Superdeformed Nuclei

R. V. F. Janssens and T. L. Khoo

Quasi-Elastic Heavy Ion Collisions

K. E. Rehm

Forward and Transverse Energies in Relativistic Heavy Ion Collisions at 14.6 GeV/c Per Nucleon

T. Abbott et al. (E-802 Collaboration)

Comparison of p + A and Si + Au Collisions at 14.6 GeV/c

T. Abbott et al. (E802 Collaboration)

A Method for Determining the Branching Ratio for the Superallowed Decay:
\(^{10}\text{C}(0^+,gs) + ^{10}\text{B}(0^+,1.74 \text{ MeV}) + e^+ + \nu\)

M. A. Kroupa, S. J. Freedman, P. H. Barker, S. M. Ferguson

Distributions of Charged Hadrons Observed in Deep-Inelastic Muon-Deuterium Scattering at 490 GeV

M. R. Adams and the Fermilab E665 Collaboration

Spin-Exchange Optical Pumping as a Source of Spin-Polarized Atomic Deuterium

L. Young, B. Zeidman and D. K. Toporkov
Proton Propagation in Nuclei Studied in the \((e,e'p)\) Reaction


Inverse Reactions and the Statistical Evaporation Model: Ingoing-Wave Boundary-Condition and Optical Models
J. M. Alexander, M. T. Magda and S. Landowne


Dynamical Effects in Pair Production by Electric Fields
A. B. Balantekin, J. E. Seger and S. H. Fricke


Quasielastic \((p,p')\) Reactions in Simplified Response Models
J. Jaenicke, G. Bertsch, G. Chanfray, H. Esbensen and P. Schuck


Threshold Electrodisintegration and Electromagnetic Form Factors of the Deuteron
R. Schiavilla and D. O. Riska


Variational Monte Carlo Calculations of the \(^2H(d,\gamma)^4\text{He}\) Reaction at Low Energies
A. Arriaga, V. R. Pandharipande and R. Schiavilla


Variational Calculations of Few-Body Nuclei
R. B. Wiringa


Unitary Meson-exchange Calculation of the \(\pi^+d\leftrightarrow pp\) Reaction
A. Matsuyama and T.-S. H. Lee


Relativistic Mean Field Theory of Nuclei with a Vector Meson Self-Interaction
A. R. Bodmer


Strong Mutual Excitation of \(^{148}\text{Nd} + ^{20}\text{Ne}\)
Cheng-Lie Jiang, Shigeru Kubono, Nobuo Ikeda, Masahiko Tanaka, Hideo Kawashima, Yoshihide Fuchi, Ichiro Katayama, Toru Nomura, and Steven C. Pieper


Relativistic Constituent-Quark Model of Nucleon Form Factors
P. L. Chung and F. Coester

Angular Distribution of Neutrons Emitted in \((^{11}\text{Li},^{9}\text{Li})\) Breakup Reactions
H. Esbensen

Light Cone Regular Vertex in Quenched QED3
Conrad J. Burden and Craig D. Roberts

Weak Proton Capture Reactions on \(^1\text{H}\) and \(^3\text{He}\) and Tritium \(\beta\) Decay
J. Carlson, D. O. Riska, R. Schiavilla and R. B. Wiringa

Rotational Bands with Identical Transition Energies in Actinide Nuclei
I. Ahmad, M. P. Carpenter, R. R. Chasman, R. V. F. Janssens, and T. L. Khoo

Meson-Exchange \(^7\text{N}\) Model and Neutral Pion Photoproduction From Proton Near Threshold
Chauchen Lee, Shin Nan Yang, and Tsung-Shung H. Lee

Nuclear Equilibrium Shapes Near \(A=100\)
R. R. Chasman

Pair Correlations Near the Neutron Drip Line
G. E. Bertsch and H. Esbensen

Meson-Exchange Calculation of the \(^7\text{N}\to\#\text{N}\) Reaction
T.-S. H. Lee and B. C. Pearce

Superdeformed and Hyperdeformed Banana Shaped Nuclides Near \(A=190\)
R. R. Chasman

Modelling the Quark Propagator
A. G. Williams, G. Krein, and C. D. Roberts

Comments on Nucleon-Nucleon Phase-Shift Analyses in the \(A\) Excitation Region
C. G. Fasano and T.-S. H. Lee

Nuclear Transparency to Intermediate-Energy Nucleons from \((e,e'p)\) Reactions
V. R. Pandharipande and Steven C. Pieper
Variational Monte Carlo Techniques in Nuclear Physics
J. A. Carlson and R. B. Wiringa
in Computational Nuclear Physics 1, Nuclear Structure, eds. K. Langanke, J. A. Maruhn, S. E. Koonin (Springer-Verlag, Berlin and Heidelberg 1991) 171-189

Many-Body Theory of Electron-Nucleus Scattering: Light Nuclei
J. Carlson, V. R. Pandharipande, and R. Schiavilla
Book Chapter in Modern Topics in Electron Scattering, eds. B. Frois and I. Sick (World Scientific, Singapore 1991) 177-218

Laser-rf Double Resonance Study of N₂⁺

Precision Measurements of the QED Effects in Helium-Like Boron
T. P. Dinneen, N. B. Mansour, H. G. Berry, L. Young, and R. C. Pardo

Stimulated Raman Measurements of the Hyperfine Structure of Y II
T. P. Dinneen, N. Berrah Mansour, C. Kurtz, and L. Young

Hfs of High-L States in ¹⁴³,¹⁴⁵Nd I by Atomic-Beam Laser-RF Double Resonance
W. J. Childs

M1, E2, and M3 hfs and Nuclear Moment Ratios for ¹⁵¹,¹⁵³Eu
W. J. Childs

Doppler-free Laser Spectroscopy of CeF and Observation of Hyperfine Structure
Y. Azuma, W. J. Childs, and K. L. Menningen
J. Mol. Spectrosc. 145, 413-419 (1991)

Sensitivity of Coulomb-Explosion Images to the Shapes of Molecular Potentials: The Case of He₂⁺⁺
D. Zajfman, E. P. Kanter, Z. Vager, and J. Zajfman

Measurement of the Distribution of Bond Angles in H₂O⁺

The Structures of C₂H⁺ and C₂H₂⁺ as Measured by Coulomb-Explosion Imaging
Precision Spectroscopic Measurements in Few-Electron Ions
R. W. Dunford, H. G. Berry, D. A. Church, T. P. Dinneen, M. Hass,
C. J. Liu, N. Berrah-Mansour, R. C. Pardo, M. L. A. Raphaelian,
L. Young, B. J. Zabransky, and L. J. Curtis

Alignment of Ne\textsuperscript{7+} Following Electron Capture by Ne\textsuperscript{8+} Ions in a Sodium Target
C. J. Liu, R. W. Dunford, H. G. Berry, and D. A. Church

Direct Observation of Hyperfine Quenching of the \textsuperscript{2}\textsuperscript{3}P\textsubscript{0} Level in Helium-Like Nickel
R. W. Dunford, C. J. Liu, J. Last, N. Berrah-Mansour, R. Vondrasek,
D. A. Church, and L. J. Curtis

Nonresonant Transfer and Excitation in Ne\textsuperscript{6+} - He Collisions at Intermediate Energies
M. L. A. Raphaelian, H. G. Berry, N. Berrah-Mansour, and D. Schneider

Production of Electron-Polarized Beams of Multiply-Charged Ions: Their Use in Tests of Fundamental Atomic Physics
C. J. Liu and R. W. Dunford

Depolarization Following Electron Capture by Highly Charged Ions in a Polarized Target
C.-J. Liu and R. W. Dunford

Lifetime Measurements in Highly Ionized Silicon
A. E. Livingston, R. G. Serpa, A. S. Zacarias, L. J. Curtis, H. G. Berry,
and S. A. Blundell

Inner-Shell Photoionization of Stored Positive Ions Using Synchrotron Radiation
S. D. Kravis, D. A. Church, B. M. Johnson, M. Meron, K. W. Jones,
J. Levin, I. A. Sellin, Y. Azuma, N. Berrah-Mansour, and H. G. Berry

Measurement of the Ratio of Double-to-Single Photoionization of Helium at 2.8 keV Using Synchrotron Radiation
J. C. Levin, D. W. Lindle, N. Keller, R. D. Miller, Y. Azuma,
N. Berrah-Mansour, H. G. Berry, and I. A. Sellin

Sequential Photoionization of Ions Using Synchrotron Radiation and a Penning Ion Trap
S. D. Kravis, D. A. Church, B. M. Johnson, J. C. Levin, Y. Azuma,
I. A. Sellin, M. Meron, K. W. Jones, M. Druetta, N. Berrah-Mansour,
H. G. Berry, and R. T. Short
Electron Transfer Collision Studies on Stored Ions Produced by Synchrotron Radiation


Direct Determination of Molecular Orbital Symmetry of H(2)S Using Polarized X-Ray Emission


Polarized X-ray Emission Studies of Methyl Chloride and Chlorofluormethanes


Anisotropy of Polarized X-ray Emission from Atoms and Molecules


Synchrotron X-ray Standing Wave Study of Sb on GaAs(110) and InP(110)


Determination of the Sb/Si(111) Interfacial Structure by Surface Extended X-ray Absorption Fine Structure and Back Reflection X-ray Standing Wave Techniques


Anisotropy of Polarized X-ray Emission from Free Molecules


Papers Presented at Meetings

Characteristics of Various Temescal Electron Beam Sources
G. E. Thomas and J. P. Greene

The Production of Molybdenum Targets for Heavy-Ion Experiments by Electron Beam Evaporation
J. P. Greene and G. E. Thomas

Evaporation Techniques for Preparing Rare-earth Targets used in Heavy-Ion Nuclear Physics
J. P. Greene and G. E. Thomas

Reflection Asymmetric Shapes in Nuclei

Single Particle States in the Heaviest Known Nuclei
I. Ahmad, R. R. Chasman, and A. M. Friedman

Bragg Curve Spectroscopy and Digital Processing
J. J. Vega, J. J. Kolata, W. Chung, D. J. Henderson, and C. N. Davids

Octupole Deformation in the Odd-Odd Nucleus $^{224}\text{Ac}$
I. Ahmad, J. E. Gindler, M. P. Carpenter, D. J. Henderson, E. F. Moore, R. V. F. Janssens, T. L. Khoo, I. G. Bearden, C. C. Foster
Population of Superdeformed Bands and Competition with Fission

Systematics of Neutron Transfer at Large Distances
A. Wuosmaa, K. E. Rehm, B. G. Glagola, T. H. Happ, W. Kutschera, and F. L. H. Wolfs

The Hg Region: Superdeformation and Other Shapes

ECR Ion Sources and Applications with Heavy-Ion Linacs
R. C. Pardo

A Very Wide Bandwidth Faraday Cup Suitable for Measuring Gigahertz Structure on Ion Beams with Velocities Down to $\beta < 0.01$
J. M. Bogaty, R. C. Pardo, and B. E. Clifft

High Electric Fields in a Superconducting RFQ Structure
J. R. Delayen and K. W. Shepard

First Tests of a Superconducting RFQ Structure
J. R. Delayen and K. W. Shepard
Design and Application Possibilities of Superconducting Radio-Frequency Quadrupoles

A. Schempp, H. Deitinghoff, J. R. Delayen, and K. W. Shepard

The ATLAS Positive-Ion Injector

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

Realizations of Polarized Targets in Storage Rings

Edward R. Kinney

A New Detector for Solar Neutrino


Nucleon Parton Distributions and Nuclear Structure

D. F. Geesaman

Polarized Gas Targets for Storage Rings

R. J. Holt

The Measurements of the Atoms' Polarization in the Drifilm Coating Storage Cell

Exclusive Nuclear Reactions: Can You Count on the Deuteron?
R. J. Holt

Superdeformation in the Mercury Region
R. R. Chasman

Sub-BARRIER Fusion and Near-BARRIER Quasielastic Scattering
J. J. Kolata, R. J. Tighe, S. H. Fricke, H. Esbensen, and S. Landowne

Nuclear Structure and Sub-BARRIER Fusion
H. Esbensen

Calculations of the Ground State of $^{160}O$
Steven C. Pieper

Low-Energy Heavy-Ion Fusion Reactions
S. Landowne

Meson-Exchange NN Model
S. Lee, S. N. Yang and T.-S. H. Lee
Spin Observables and Electromagnetic Excitations of Nucleon Resonances
T.-S. H. Lee and S. Nozawa

M1 Decay of the $2^3S_1$ State of Helium-Like Bromine

Polarization and Anisotropy of X-ray Emission from Molecules
P. L. Cowan
Distribution for ANL-92/16

Internal:

Ahmad, I.       Henderson, D. J.       Rehm, K. E.
Azuma, Y.        Henning, W. P.       Ringo, G. R.
Back, B. B.      Holt, R. J.         Schiffer, J. P.
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