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ANL-93/12

Physics Division Annual Review
April 1, 1992–March 31, 1993

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PHYSICS DIVISION ANNUAL REVIEW

April 1, 1992 -- March 31, 1993

Walter F. Henning
Director

August 1993

Preceding Annual Reviews

ANL-90/18	1989-1990
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ANL-92/16	1991-1992

Edited by Karen J. Thayer

FOREWORD

The past year has seen several developments of importance to the Physics Division's research program. Most importantly, the new positive-ion injector (PII) of ATLAS was completed and successfully commissioned. High-quality beams of good intensity are now available for ion masses up to uranium. By May 1993, beam currents on target up to 5 particle nanoampere of ^{238}U at 6.3 MeV per nucleon have been achieved.

In parallel with the completion of the ATLAS accelerator, several important pieces of experimental equipment have been constructed which take advantage of the new accelerator capabilities. In particular, APEX, the ATLAS positron experiment, will study the peaks found in electron-positron coincidences in collisions in very heavy ions over the past decade at GSI. APEX is a joint effort of seven university groups and Argonne. The past year has also seen the successful commissioning of the completed Fragment Mass Analyzer (FMA), testing of associated detector systems, and first experiments. This new device, which has demonstrated mass resolutions of better than 1 in 500 for medium-heavy compound nuclei, is now used in a large fraction of the experiments at ATLAS.

A major part of the effort in heavy-ion research was devoted to gamma-ray experiments. The focus of this work is on the study of superdeformation, especially in the mass-200 region. This region of superdeformation was first investigated at ATLAS and provides a very clean example of this new form of nuclear symmetry. The experiments in this mass region are now focused on the subtle effects of superdeformation and a model has been developed which follows the history of superdeformation bands from formation to decay. The model accounts successfully for many observations including sudden decay out of the band. In addition to experiments at the local Argonne/Notre Dame BGO setup, experiments are being performed at the new-generation gamma detector arrays, EUROGAM at Daresbury and, more recently, GAMMASPHERE at Berkeley. Considerable effort was devoted to design, construction and testing of GAMMASPHERE. Argonne took on responsibility for procurement and testing of the BGO detectors, for design and construction of several scattering chambers, and for development of parts of the software.

Charged-particle experiments have continued using the excellent timing properties of ATLAS beams. This research effort was greatly helped by the installation of the new radiation interlock system (ARIS) which made possible access to the experimental stations with the beam on target. The study of exotic cluster states in light nuclei has continued using the Argonne highly-segmented silicon detector array. The availability of heavier beams from the PII now allows to use the advantages of inverse kinematics for heavy particle detection. The studies of subbarrier fusion cross sections have been pursued using the technique of a gas-filled magnet.

In accelerator mass spectrometry (AMS) the first measurement of 76,000 yr ^{59}Ni in lunar material was accomplished using the full stripping technique. This opened the possibility of measuring the integral flux of solar cosmic-ray alpha particles over the past 200,000 years. The noble gas radioisotope ^{39}Ar (269 yrs) was measured for the first time at the extreme low level of 1×10^{-15} with AMS.

In addition to the development efforts towards experimental equipment, an ongoing development program continues on rf superconductivity. The impressive advance illustrated with the just-completed PII injector in extending superconducting niobium accelerating structures to low-beta ions is of interest for possible future radioactive beam facilities and possibly of industrial significance. Efforts include construction of a prototype superconducting niobium RFQ, and work on an extended multi-gap structure as an extension of the PII resonator concept.

An exciting medium-energy nuclear physics program is addressing topics of wide interest including 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 based on experiments involving electron and deep-inelastic muon scattering.

Experiment 665 at Fermilab uses deep-inelastic scattering of 490-GeV muons to study the structure of the nucleon and its modification in nuclear matter. Among the interesting results emerging are the saturation of shadowing of nuclear targets at very low x, evidence for the running of the strong coupling constant in the transverse momentum distribution in 2 jet events, exclusive vector meson production, Bose-Einstein correlations, and inclusive hadron distributions from deep inelastic scattering.

The Argonne medium-energy physics program has a major presence in the program at CEBAF. In addition to preparing several approved experiments with ANL spokespersons, staff members are actively involved in the construction of a broad-purpose short-orbit spectrometer (SOS) to be made generally available to users at CEBAF. Commissioning of the SOS is planned for 1994.

Considerable effort has been devoted to developing a new technology for producing polarized hydrogen and deuterium targets employed in electron storage rings to study spin-dependent phenomena at high-momentum transfer. The polarized deuterium gas target has been installed in the circulating electron beam at the VEPP-3 electron storage ring at Novosibirsk to study polarization effects in elastic and inelastic scattering.

The medium-energy group is involved in a proposal (HERMES) to study the spin structure of the nucleon using internal polarized targets in the HERA electron storage ring at the DESY Laboratory in Germany. Activities involving the NPAS program at the Stanford Linac Accelerator Center are approaching their conclusive phase. Analysis of data from measurements of the photodisintegration of the deuteron at photon energies up to 4.2 GeV is nearing completion, as is an experiment to search for color transparency.

In the study of weak interactions at low energy, the most noteworthy development was the completion of the search for a 17-keV neutrino whose existence has been the subject of intense controversy. The Argonne experiment employs a superconducting solenoidal beta spectrometer, a novel technique for reducing the effects of back-scattering. There is no evidence for a 17-keV neutrino and an upper limit on the branching ratio is below 0.25%. With the announcement of these results, proponents of the 17-keV neutrino have retracted their claims. This project was the senior thesis of Justin Mortara and was awarded the prestigious APS Apker Award for undergraduate work in 1992.

The Argonne theory program is addressing many questions of interest to current problems in nuclear physics, including the roles of mesons, nucleon resonances, and quark-gluon degrees of freedom in determining nuclear dynamics. Theoretical models are being developed for the energy regions accessible to CEBAF aiming at testing various QCD-based predictions of the excitations of nucleon resonances. The consequences of chiral symmetry in near-threshold pion production have been investigated. A systematic approach to account for the short-range pion absorption mechanisms has been developed by extending Weinberg's effective πN chiral Lagrangian to nuclei. A program has been initiated to investigate the properties of an extended meson system which is expected to be the main component of the hadronization of quark-gluon plasma that one hopes to see at RHIC.

Furthermore, fundamental problems concerning the connections between relativistic particle quantum mechanics and relativistic quantum field theory have been investigated. In addition, a practical alternative to lattice gauge theory applicable in calculating hadron properties within QCD is being developed.

In the area of nuclear structure, cranked shell-model calculations for heavy nuclei, and detailed studies of fragmentation reactions in very neutron-rich nuclei (^{11}Li) have been carried out. The shell-model calculations near mass 200 continue the successful work which was originally the first to predict superdeformation in this mass region.

The Atomic Physics research program in the Argonne Physics Division has focused on two principal areas of research: (a) Accelerator-Based Atomic Physics; (b) Synchrotron Radiation-Based Atomic Physics. Collisions of fast heavy particles are an integral part of the atomic structure program whose aim it is to test relativistic and quantum electrodynamics (QED) atomic applications. Interesting results have been obtained in spectroscopic and lifetime measurements. High-precision laser excitation of fast-ion beams at the BLASE facility has continued with emphasis on studies of hyperfine structure of metallic and rare-earth ions. New theoretical developments in this area have shown greatly improved comparisons between the measured and calculated hyperfine constants. In an initial set of measurements at BLASE of the decay curve of the laser-excited resonance transition in cesium, a lifetime value with a precision of better than 1% was obtained. This is important in comparing theory and experiment for the parity-violation contribution in cesium.

In the synchrotron radiation-based program, experiments using the X-24A beamline at the Brookhaven National Synchrotron Radiation Source were performed including accurate measurements of the ratio of double-to-single ionization of helium from high-energy photons, an important test of fundamental theory, measurements of absolute photoionization cross sections, and multi-electron excitation through a combination of diverse experimental techniques. A major emphasis of the synchrotron radiation-based work is the design and development of beamlines at the APS.

Finally, the program of Coulomb-explosion studies of small molecular ions at the Dynamitron has entered a very exciting stage. Measurements of structures of cooled light diatomic and triatomic ions were completed yielding hitherto unavailable information on the structure of these molecules.

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 60 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.

W. Henning

Walter Henning
Director, Physics Division

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NUCLEAR PHYSICS RESEARCH

I. HEAVY-ION RESEARCH

With the completion of the positive-ion injector, the heavy-ion accelerator ATLAS is now capable of accelerating all ions up to uranium with excellent beam qualities and easy energy variability. This new capability of the machine opens opportunities for experiments using novel and sophisticated equipment installed in past years. The heavy-ion research program of the Argonne Physics Division spans a wide range from studies of heavy-ion elastic scattering to the search for nuclei far away from the valley of stability and the search for exotic new particles in collisions between very heavy nuclei. ATLAS is a national user facility with 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 effort come from university groups. The gamma-array, which has a very active research program, is a joint project between Argonne and the University of Notre Dame. Outside groups are 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 major part of the research effort is devoted to gamma-ray experiments. The focus of this work is on the study of superdeformation, especially in the mass-190 region. This was discovered at ATLAS four years ago and 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 experiments in this mass region have now gone into a stage where more subtle effects of superdeformation can be investigated.

For all superdeformed nuclei in the mass-190 region, the dynamic moments of inertia are observed to increase with rotational frequency which can be explained within the framework of cranked shell-model calculations. In a recent experiment at ATLAS, six superdeformed bands were found in ^{192}Tl. While four of these bands have a dynamic moment of inertia which increases with rotational frequency, two of the bands showed a dynamic moment of inertia which is constant. This result can be understood in terms of Fermi blocking of quasi-particle alignments and represents the first strong experimental evidence for this alignment picture.

Another unexpected observation was the distinct change in the slope of the dynamic moment of inertia, at the highest frequencies in ^{190}Hg and ^{196}Pb. This result is interpreted as evidence for a band interaction analogous to the one responsible for the backbending phenomenon in the rare-earth nuclei.

In order to better understand superdeformation, a model was developed which follows the history of superdeformation bands from formation to decay. The model accounts successfully for the entry distributions, the population intensities of superdeformation bands, and the variation of intensities with spin. It also explains the sudden decay out of the band.

The group has also participated in two experiments with the next-generation γ-detector array EUROGAM at Daresbury, investigating the decay out of the superdeformed band in ^{192}Hg and the structure of neutron-rich fission fragments.

The charged-particle research was helped greatly by the installation of the new radiation interlock system (ARIS) which made possible access to the experimental stations with beam on target. Thus experiments which use the excellent timing properties of the ATLAS beams could resume. The experimental program at the Fragment Mass Analyzer (FMA) has started and there are many proposals from the user community for experiments with this new device. In a recent FMA experiment, a mass resolution of 525:1 and beam suppression ratios of 10^{-11} were obtained. The possibility of mounting 10 Compton-suppressed Ge- detectors around a special scattering chamber at the FMA allowed mass-gated γ-γ coincidence measurements with much higher efficiencies than possible so far.

The study of exotic cluster states in ^{24}Mg has continued using the highly segmented Si-detector array, with the main emphasis on determining the angular momenta contributing to the resonance-like structure decaying into 6 α-particles. The availability of heavier beams from the positive-ion injector also allowed us to use the advantages of inverse kinematics for heavy particle detection, and first experiments in the field of deep-inelastic reactions at subbarrier energies were performed.

We have measured subbarrier-fusion cross sections in the system $^{58,64}Ni + ^{92,100}Mo$ using the technique of a gas-filled magnet which is a very efficient method allowing good separation from the elastically scattered particles. These systems are of great interest since so far no theoretical models are able to reproduce the large experimental fusion enhancement.

In Accelerator Mass Spectrometry (AMS), the first measurement of 76,000 year ^{59}Ni in lunar material was accomplished using the full-stripping technique. This opened the possibility of measuring the integral flux of solar cosmic-ray α-particles over the past ~ 200,000 years. Using the ECR source, the concentration of 269 year ^{39}Ar in atmospheric argon at the extremely low level of 1×10^{-15} was measured.

In the area of secondary beams we are pursuing the production of a ^{17}F beam from the inverse $p(^{17}O,^{17}F)n$ reaction Test measurements with a rotating polyethylene target were performed in order to study the lifetime of these foils with very intense beams. The studies of crystalline beams contained in ion traps or storage rings continued, and comparisons with experimental data were performed.

For APEX, the ATLAS positron experiment, the past year saw the completion of the final assembly of the apparatus and considerable progress toward the complete installation of the detector systems was made. The APEX experiment, which will study the peaks found in electron-positron coincidences in collisions between very heavy ions, is a joint effort of six university groups and Argonne. The intent of the experiment is to resolve the origin of these peaks. All detector systems were tested with beams from ATLAS, including ^{238}U beams, and measurements are in progress.

The Argonne gamma group has, from the beginning, been heavily involved in the GAMMASPHERE project, in the design, as well as in the construction and testing of this new device. Argonne has taken on responsibility for procurement and testing of the BGO detectors, for the design and construction of the scattering chamber, and for the development of parts of the software.

A. CHARGED-PARTICLE STUDIES

The excellent beam quality and easy energy variability make ATLAS an ideal tool for charged-particle reaction studies. In the past year the research focussed on two major areas: (a) the study of nuclear reaction mechanisms at energies in the vicinity of the Coulomb barrier and (b) studies of the production and decay of exotic nuclear cluster states in s-d-shell nuclei. In both fields novel techniques have been employed which allowed the study of the reaction processes with much-improved efficiency. A gas-filled magnet was used to separate evaporation residues at forward angles from the intense yields of elastically scattered beam particles. Using this technique, integrated fusion cross sections down to 100 μb were measured. For the multi-particle decay measurements of exotic cluster states, a detector array consisting of four 5×5 cm^2 Si strip detectors with 4×256 pixels was employed. With the availability of heavier beams from the positive-ion injector the first experiments using inverse reactions with medium-mass projectiles were performed.

a. Quasi-Elastic Reactions, Deep-Inelastic Reactions and Fusion

Many reaction mechanism studies have shown that especially at bombarding energies close to the barrier strong correlations between the various reaction modes (inelastic scattering, transfer reactions, deep-inelastic scattering and fusion) exist. One of the goals of the research program at ATLAS is to gain a better understanding of these correlations. The availability of beams of different isotopes and the easy energy variability are essential for these types of studies. In the area of subbarrier fusion, a large enhancement factor for the system $^{64}Ni + ^{100}Mo$ was measured previously which could not be explained by any theoretical model. Using the technique of a gas-filled magnet we confirmed this enhancement and extended these measurements to the systems $^{58,64}Ni + ^{92,100}Mo$. All of them exhibit much higher fusion cross sections than expected from theoretical (coupled-channels) calculations. Measurement of quasi-elastic transfer cross sections in these systems were performed in order to study the coupling strength to these channels. These experiments were done at the split-pole spectrograph in inverse kinematics with ^{92}Mo beams from the positive-ion injector and surprisingly small transfer yields were observed. These results indicate that subbarrier fusion involving medium-mass nuclei is not understood theoretically.

The advantages of inverse kinematics were used in an experiment studying the strength of deep-inelastic reactions at subbarrier energies in the system $^{136}Xe + ^{64}Ni$.

The investigations of the charge-state dependence of internal conversion and fluorescent yields in few-electron systems continued with an experiment using a 735-MeV ^{83}Kr beam from the positive-ion injector. Relativistic wave function codes have been modified which allow the calculation of conversion coefficients in highly charged ions. First experiments have been performed to study quasi-elastic scattering of the extremely neutron-rich nuclei ^{11}Li and ^{14}Be produced at the MSU fragment separator.

a.1. Measurement of Fusion Cross Sections for $^{58,64}Ni + ^{92,100}Mo$ Using the Gas-Filled Magnet Technique (K. E. Rehm, J. Gehring,* B. G. Glagola, D. J. Henderson, W. Kutschera, M. Paul,* F. Soramel,‡ and A. H. Wuosmaa)

The enhancement of the cross sections for heavy-ion-induced fusion reactions at sub-barrier energies was studied extensively during the last 10 years. In addition to the increased fusion probability, a strong dependence of the fusion yield on the neutron

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*Resident Graduate Student from the University of Chicago,†Hebrew University, Israel, ‡University of Padova, Italy number in projectile and target was observed for various lighter systems, (e.g. Ni + Si, Ni + S, Ni + Ni). We studied the fusion cross sections in the heavier systems $^{58,64}Ni + ^{92,100}Mo$ using the gas-filled magnet technique.

The experiments were performed with Ni beams of 204-260-MeV incident energy in the split-pole spectrograph, which was filled with N_2 at a pressure of 0.3 torr. Because of charge-changing collisions between the ions and the residual gas molecules, the charge-state distributions for the evaporation residues (ERs) and the projectiles are centered around an average charge state $\bar{q}$, with a width that is only a few cm wide as measured in the focal plane of the spectrograph. The difference in the magnetic rigidity and the time of flight between the ERs and the incident ions allows for a clean separation of the fusion products from the elastically scattered beam particles even at very small scattering angles.

The system $^{64}Ni + ^{100}Mo$ was studied previously using γ-ray techniques and a very large fusion enhancement was observed, that could not be explained within the coupled-channels formalism. Our measurements confirm the results for this heavy system. The results involving the more neutron-deficient nuclei ^{92}Mo and ^{58}Ni also show large fusion enhancements that cannot be explained by coupled-channel effects, including inelastic excitations. We are presently working on a comparison of the results with various theoretical models. The influence of transfer reactions is also being investigated (see contribution A.a.2.).

a.2. <u>Transfer Reactions in the Systems ^{58,64}Ni + ^{92,100}Mo</u> (K. E. Rehm, J. Gehring,* B. G. Glagola, C. L. Jiang,† W. Kutschera, F. L. H. Wolfs,‡ and A. H. Wuosmaa)

In order to explain the large subbarrier fusion enhancement observed in the systems $^{58,64}Ni + ^{92,100}Mo$ (see previous contribution) within a coupled-channels description matrix elements for inelastic excitations are required that are typically 50% larger than found experimentally. We have investigated whether transfer reactions have sufficient strength for these systems in order to explain this discrepancy. The experiments were performed in inverse kinematics with Mo beams and Ni targets at the split-pole spectrograph. The target-like reaction products were detected at forward angles in the focal-plane detector and a complete separation of the products according to their mass and charge was achieved. The systems $^{100}Mo + ^{58,64}Ni$ were studied with beams from the tandem injector, while for the ^{92}Mo + Ni systems beams from the new positive-ion injector were used in the experiments. The results for ^{100}Mo + Ni were completely analyzed and surprisingly small transfer cross sections were observed. The analysis of the ^{92}Mo + Ni experiment is still in progress.

These results indicate that the strength of the transfer reactions is too small to explain the large subbarrier fusion enhancement in a coupled-channel description.

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a.3. Neutron Transfer at Large Distances in Spherical and Deformed Systems

(K. E. Rehm, B. G. Glagola, W. Kutschera, F. L. H. Wolfs,* and A. H. Wuosmaa)

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. This was studied for a variety of reactions involving spherical and deformed nuclei. The experiments were performed at the split-pole spectrograph with a focal-plane detector which allowed a complete separation of the reaction products according to their mass and charge. The majority of one-neutron transfer reactions can be well described by the simple tunneling model. The transfer probabilities for two-neutron transfer reactions, however, show deviations from the semiclassical predictions with a disagreement that increases at higher bombarding energies (see Fig. I-1). These deviations can be explained by the more localized form factors for multiparticle transfer reactions which require an analysis of the data within the diffraction model. A publication of the results has been submitted.

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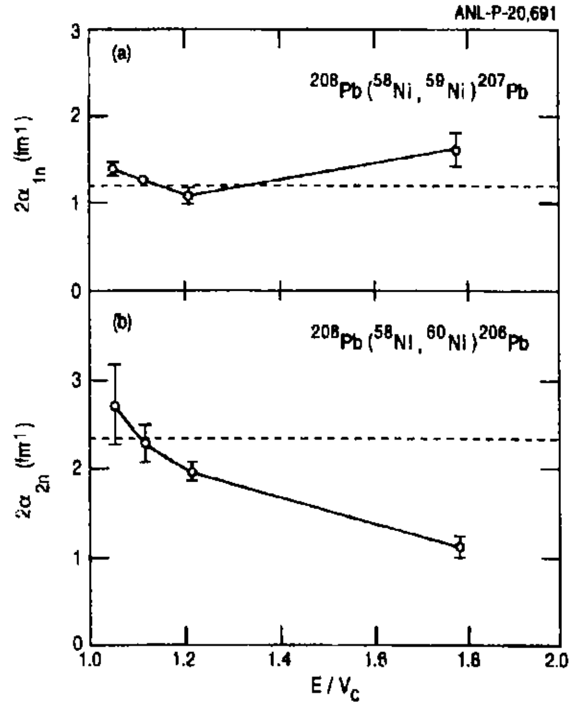

Fig. I-1. (a) Experimental decay constant 2α for the one-neutron transfer reaction $^{208}Pb(^{58}Ni,^{59}Ni)^{207}Pb$ as function of the energy above the Coulomb barrier E/V_C. The dotted line is the decay constant calculated from the corresponding binding energy. (b) Same as (a), but for the two-neutron transfer $^{208}Pb(^{58}Ni,^{60}Ni)^{206}Pb$.

a.4. Study of the Neutron- and Proton-Transfer Strength in $^{54}Fe + ^{86}Kr$
(K. E. Rehm, C. L. Jiang,* B. G. Glagola, T. Happ,† F. Scarlassara,‡ and A. H. Wuosmaa)

Neutron-transfer reactions induced by medium-weight projectiles were studied extensively in the past and a systematic behavior of the transfer strength and the energy dependence for these reactions was observed. This behavior can be explained in a simple semiclassical picture which is based on kinematic matching conditions and the tunneling of neutrons through a potential barrier. Charged-particle transfer reactions, because of their smaller cross sections, so far have been studied only for a few cases. We have started to investigate the relative strengths of neutron- and proton-transfer reactions in the system $^{54}Fe + ^{86}Kr$ which involves nuclei with closed neutron shells. The experiment was performed in inverse kinematics with a ^{86}Kr beam of 307 MeV and a ^{54}Fe target. The reaction products were detected with the split-pole spectrograph and its focal-plane detector allowing the identification of individual elements and isotopes. The data were completely analyzed. Despite the closed-neutron shell structure of both projectile and target, one-neutron transfer (^{54}Fe,^{55}Fe) is still the strongest channel, followed by the one-proton channel (^{54}Fe,^{53}Mn) and the two-neutron transfer (^{54}Fe,^{56}Fe) which have about equal strength. In the future we plan to compare these results with data for the system $^{92}Mo + ^{48}Ca$.

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‡ University of Padova, Italy

a.5. Quasi-Elastic Reactions of $^{28}Si + ^{208}Pb$ at Energies of 10 and 15 MeV/A
(K. E. Rehm, D. G. Kovar, S. Dixit,* J. J. Kolata,* R. A. Kryger,* A. Morsad,* R. Tighe,* X. J. Kong,* W. K. Chung,* and R. J. Vojtech*)

In order to study the energy dependence of the heavy-ion optical potential measurements of elastic and inelastic scattering as well as transfer reactions in the system $^{28}Si + ^{208}Pb$ were performed at bombarding energies of 280 and 420 MeV. Together with earlier high-resolution measurements, data for the system $^{28}Si + ^{208}Pb$ are now available covering the energy range from 5.4 MeV/A to 15 MeV/A. The experiment was performed at the split-pole spectrograph. Good mass- and Z-separation for the various ejectiles was achieved. The data were compared with the results of coupled-channel calculations with the goal of obtaining a consistent set of optical model parameters that can describe elastic and inelastic scattering. The data were completely analyzed and a paper with the results was submitted for publication. This experiment is part of the thesis project of S. Dixit (University of Notre Dame).

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a.6. Quasi-Elastic Reactions in the System $^{37}Cl + ^{208}Pb$ (K. E. Rehm, S. Dixit,* M. Belbot,* W. K. Chung,* J. J. Kolata,* K. Lamkin,* R. Tighe,* and M. Zahar*)

Elastic and inelastic scattering for the systems $^{28}Si + ^{208}Pb$ was studied with good resolution in the energy range E_{lab} = 152-420 MeV and a consistent set of optical potential parameters was established. Because of the strong excitation probability of the 2^+ state in ^{28}Si a coupled-channels treatment is necessary which complicates the fitting procedures. We therefore performed several experiments with the system $^{37}Cl + ^{208}Pb$ at E_{lab} = 190, 330 and 430 MeV where the strongest inelastic channel is the excitation of the 3^- state in

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^{208}Pb. These experiments were performed at the split-pole spectrograph with the parallel-plate Bragg-curve focal-plane detector which allowed a complete separation of elements and isotopes around ^{37}Cl. The data were analyzed and a publication is being prepared. This experiment is part of the thesis project of S. Dixit (Notre Dame).

a.7. **Kinematic Coincidence Measurements of Deep Inelastic Reactions in $^{136}Xe + ^{64}Ni$ near the Coulomb Barrier** (J. Gehring,* M. Freer, D. Henderson, K. E. Rehm, J. P. Schiffer, M. Wolanski,* and A. Wuosmaa)

Deep inelastic reactions have been observed recently in heavy-ion collisions at energies close to and even below the Coulomb barrier. This is of interest because standard friction models of deep-inelastic reactions fail to explain the energy dissipation at low-incident energies.

We have undertaken the measurement of cross sections and angular distributions for deep-inelastic reactions at several energies near and below the barrier in the system $^{136}Xe + ^{64}Ni$. This system was chosen for nuclear structure reasons. ^{136}Xe is at the N = 82 closed neutron shell and ^{64}Ni is at the Z = 28 closed proton shell. The measurements were performed with three large-area gas detectors in a kinematic coincidence arrangement. The time-of-flight and the scattering angles of the products of binary reactions were recorded. This allows one to reconstruct the kinematics of the reaction, i.e. the masses of the outgoing nuclei and the reaction Q-value.

The data are currently being analyzed and should provide information on whether the mechanism for energy dissipation at energies near the barrier is in fact different from the traditional friction forces invoked at higher energies. Some theories of heavy-ion interactions predict a dependence on the neutron number of projectile and target. Hence, we plan to extend the measurements to a neutron-deficient system such as $^{128}Xe + ^{58}Ni$.

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a.8. **Population Patterns in Deep Inelastic Heavy-Ion Reactions** (M. P. Carpenter, R. G. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, I. G. Bearden,* B. Fornal,† R. H. Mayer,† D. Nisius,† M. Sferrezza,† R. Broda,† P. J. Daly,† Z. W. Grabowski,† and F. Soramel‡)

We have performed extensive product yield determinations by in-beam, off-beam and radioactivity measurements for the reactions of $^{122,124}Sn$ targets with ^{76}Ge and ^{80}Se ions, at energies 10-15% above the Coulomb barrier, The results include the following yields: (1) 10^+ and $19/2^+$ μs isomers in $^{118-124}Sn$, (2) the ^{123}Sn and ^{125}Sn $3/2^+$ "ground states" from radioactivity, (3) eight high-spin ß-decay isomers in $^{116-123}In$, and (4) several fusion-evaporation products. One firm and striking result is that the 10^+ and $19/2^+$ isomers in the seven nuclei from ^{118}Sn to ^{124}Sn are populated with comparable cross sections from the ^{124}Sn target.

The overall distribution of yields as a function of A and Z was derived from γ–γ coincidence intensities between the 2^+-0^+ transition and all g rays feeding the 2^+ state directly in all identified even-even nuclei (see Fig. I-2). Analysis of these distributions gave an estimate of

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the average number of neutrons evaporated from the excited reaction products which was then used to extract the pattern of primary products. This pattern may be broadly understood in terms of N/Z equilibration in the dinuclear system formed in heavy-ion collisions. Calculated minimum potential energy surfaces can be used to explain the gross features of the observed yield pattern as well as to predict the outcome of future experiments using other target-projectile combinations. For example, yrast states in tin nuclei with A > 124 were not populated in the $^{124}Sn + ^{80}Se$ reaction, but considerations of N/Z equilibration indicate that $^{125-127}Sn$ nuclei should all be seen in an upcoming $^{124}Sn + ^{136}Xe$ study at ATLAS. A discussion of these results is being prepared for publication.

a.9. <u>Study of the Energy Dependence of Multiparticle Transfer Reactions in the System $^{76}Ge + ^{186}W$</u> (J. Gehring,* K. E. Rehm, C. N. Davids, R. V. F. Janssens, F. L. H. Wolfs,† G. E. Körner,‡ and H. J. Körner‡)

Neutron-rich nuclei in the Fe-Ge region are important for a better understanding of the r-process in nucleo-synthesis. However, experimentally these nuclei are difficult to produce since they have very small production cross sections in the fission process. We have investigated to what extent deep-inelastic reactions can be used in order to produce them.

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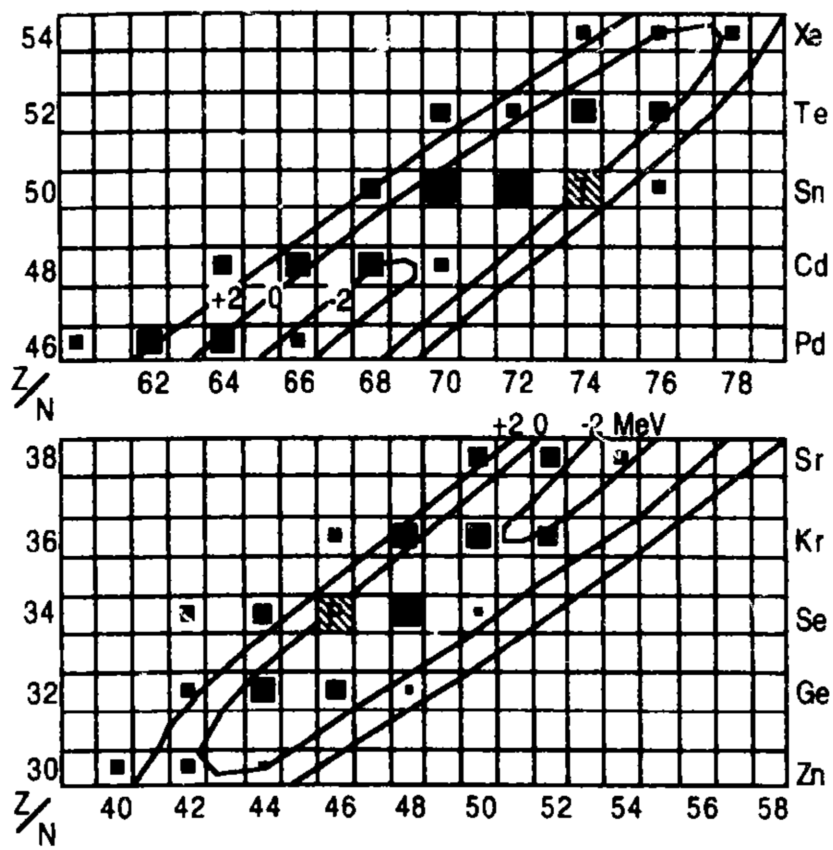

Fig. I-2 Relative yields determined for even-even products of the reaction ^{124}Sn + 344 MeV ^{80}Se. Target and projectile nuclei are labelled. The larger yields are well correlated with the minimum nuclear potential energy contours calculated for this dinuclear system.

The production cross sections for these nuclei depend critically on the bombarding energy. While the yields for multi-particle transfers increase with bombarding energy, the survival probability decreases since neutron-rich nuclei decay easily via neutron evaporation. We have therefore studied the production cross sections for neutron-rich Fe-Co-Ni nuclei as a function of the bombarding energy. The experiments were performed with ^{76}Ge beams of 430, 520 and 680 MeV in the split-pole spectrograph with the parallel-plate avalanche Bragg-curve detector in its focal plane. This system allowed a complete determination of mass, nuclear charge, atomic charge state, and reaction Q-value. The data have been completely analyzed. The production cross sections for the different elements and isotopes are presently being compared with the predictions of various theoretical models.

a.10. Study of the Charge-State Dependence of Internal Conversion Rates in ^{57}Fe (I. Ahmad, B. G. Glagola, W. Henning, W. Kutschera, K. E. Rehm, J. P. Schiffer, D. Banes,* J. Copnell,* and W. R. Phillips*)

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 that change their charge because of the internal conversion process during transit through the magnetic field are displaced in the focal plane by an amount that depends on the point in the spectrometer at which IC occurs. The analysis of the data has been completed. For comparison with theoretical predictions, a program was developed that calculates conversion coefficients from relativistic electron wave functions for highly stripped atoms. A paper has been accepted for publication.

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a.11. 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. Copnell,† and W. R. Phillips†)

An experiment was performed to measure L-shell internal conversion coefficients $\alpha_L(q)$ in highly-stripped ^{83}Kr ions of charge state q = 29-33. These measurements give information on changes in L-shell electron wave functions as electrons are successively removed and thus provide tests of relativistic mean field predictions of electron orbitals. The transition between the 9.4-keV (metastable) first excited state and ground state of ^{83}Kr is predominantly magnetic dipole (electric quadrupole to magnetic dipole intensity ratio = $1.7(2) \times 10^{-4}$) and is highly converted, chiefly in the L-shell with a small fraction in the M-shell.

A secondary beam of ^{83}Kr, in which a fraction of the nuclei was in the excited 9.4-keV state, was produced by Coulomb excitation of 735-MeV ^{83}Kr ions from the ATLAS accelerator. The beam, scattered from a 150-μg/cm^2 Au target at a laboratory angle θ_L = 22°, was analyzed in the split-pole magnetic spectrometer. The pattern of events in the focal plane was comprised of large peaks corresponding to each ionic charge, and events between these peaks corresponding to ions that underwent internal conversion during their path through the spectrometer. A total of 13×10^6 events of 12-parameter data were recorded.

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The spectrum is dependent upon the fraction of ions in the nuclear metastable state, the total number of ions, and the decay constant, for each initial atomic charge state. The analysis was performed by varying these parameters in a multi-dimensional χ^2 minimization between the experimental spectrum and a Monte-Carlo simulation. Width and tail shape parameters from the experimental spectrum are also incorporated into the calculation. The analysis is currently in progress.

Calculations of the internal conversion coefficients were performed, which determine largely the decay constants, as a function of charge state, assuming known atomic configurations with which to compare the experimental results. These used discrete atomic wavefunctions obtained from the Multi-Configurational Dirac-Fock code, GRASP, that incorporates a full treatment of the exchange potential as opposed to the more conventional Slater exchange.

a.12. Quasielastic Scattering Measurements with Radioactive Beams of A = 11 and A = 14 Isobars[1] (A. H. Wuosmaa, J. J. Kolata,* M. Zahar,* R. Smith,* K. Lamkin,* M. Belbot,* R. Tighe,* B. M. Sherrill,† N. A. Orr,† J. S. Winfield,† J. A. Winger,† S. J. Yennello,† and G. R. Satchler‡)

The study of the interactions of so-called "neutron halo" nuclei, such as ^{8}He, ^{11}Li, and ^{14}Be have recently attracted a great deal of attention. Large enhancements of the total interaction cross sections for these nuclei incident upon a variety of targets suggest that their structure
can be described by a few very loosely bound neutrons orbiting about a more tightly bound inert core. This picture has specific implications for the elastic and quasielastic scattering cross sections for systems involving these nuclei. For the system ^{11}Li + ^{12}C, enhancements as large as a factor of four for the elastic scattering cross section above the typical Rutherford value are expected, in part due to very strong nearside-farside interference.

At the National Superconducting Cyclotron Laboratory at Michigan State University, beams of these radioactive ions are available from the A1200 fragment separator, and a program to study the elastic scattering of several of these radioactive ion beams on ^{12}C was undertaken. The elastic scattering and fragmentation of ^{11}Li, ^{11}C, ^{11}Be, and ^{14}Be on ^{12}C was measured at energies of 60 MeV/nucleon. Particle fluxes of ~ 2000/sec for ^{11}C, 1000/sec for ^{11}Be, 300/sec for ^{11}Li, and 100/sec for ^{14}Be bombarded ^{12}C targets of thicknesses ranging from 100 to 500 mg/cm^2. The scattered nuclei were detected at angles ranging from 0° to 10° in the laboratory using three detector telescopes. Each telescope consisted of a double-sided silicon strip detector (see E.e.) providing ΔE and X-Y position information, and a 6-cm × 6-cm CsI crystal which served as an E detector. In some cases, a second 5 × 5-cm 300- micron-thick silicon detector was used to provide additional ΔE information. Due to the rather large beam spot, two parallel-plate avalanche counters were used at the entrance of the scattering chamber before the target to perform ray-tracing of the incident particles.

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*University of Notre Dame, †NSCL, Michigan State University, ‡Oak Ridge National Laboratory, [1]J. J. Kolata, M. Zahar, R. Smith, K. Lamkin, M. Belbot, R. Tighe, B. M. Sherrill, N. A. Orr, J. S. Winfield, J. A. Winger, S. J. Yennello, G. R. Satchler, and A. H. Wuosmaa, Phys. Rev. Lett. 69, 2631 (1992).

The results of ^{11}Li + ^{12}C elastic scattering are in good agreement with the predictions of coupled-channels calculations. These calculations are performed using potentials derived from a folding model with a Hartree-Fock density for ^{11}Li. Large enhancements in the elastic scattering cross section were observed relative to the Rutherford value at forward angles. The data for ^{11}Li and ^{11}C have been published. The ^{14}Be + ^{12}C data are still being analyzed at the University of Notre Dame.

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. These cluster states have many interesting properties, including very large deformations and unusual decay modes. The nuclear structure of these cluster configurations can also have a profound impact on reactions involving such light nuclei. Examples of studies of this type include 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 5×5-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. A number of additional experiments are planned, as well as are several improvements to the detector array and readout system.

b.1. Reaction Mechanism in the Formation of ^{12}C - ^{12}C Cluster States in ^{24}Mg

(M. Freer, A. H. Wuosmaa, and R. R. Betts)

The symmetric fission of ^{24}Mg following inelastic scattering from ^{12}C targets was found to arise from specific states in the excitation energy interval 20 to 30 MeV. Measurements of the angular momenta of these states appear to demonstrate that the fissioning nucleus is extremely deformed. Such deformed structures are predicted by several calculations. However, these were associated with exotic particle-hole excitations which are unlikely to be populated through direct inelastic excitation, and thus the reaction mechanism for the population of such states would seem to have to be more complex.

In order to resolve the question of the reaction mechanism, we measured the primary angular distribution of the excited ^{24}Mg ejectile involved in the breakup reaction. Such a measurement requires, for the detection system, extensive angular coverage and a wide energy acceptance. This experiment was the follow up to the commissioning of the four double-sided strip detectors (DSSDs) and the associated electronics, performed in the previous year with the same reaction. Coincidence data were taken with an array of four DSSDs augmented with four quad detectors. These quad detectors were of similar dimensions to the DSSDs but lacked the high segmentation, the front side of the detector being divided into four quadrants. These detectors were placed directly behind the DSSDs and were employed to veto events in which particles penetrated the DSSDs, thus reducing the load on the data stream from the prolific number of alpha - alpha coincidences. The detector array provided coverage of laboratory angles from 6 to 53 degrees and energies above 3 MeV, which for the 170-MeV ^{24}Mg beam provided almost complete coverage of the range of center-of-mass angles with an efficiency of 7 to 10 percent. These data are presently being analyzed.

b.2. Further Study of the $^{12}C + ^{12}C \rightarrow$ 6 Alpha Reaction (A. H. Wuosmaa, M. Freer, and R. R. Betts)

Previous studies[1] of the inelastic scattering reaction $^{12}C + ^{12}C \rightarrow {}^{12}C(0_2^+){}^{12}C(0^+)$ identified a strong resonance-like feature in the excitation function for this channel, peaked at a center-of-mass energy of E_{cm} = 32.5 MeV. The excitation energy in the composite system ^{24}Mg (E_x = 46.4 MeV), as well as the dominant angular momenta (14-16 $\hbar$), suggest that this structure could be related to the population of alpha-particle chain configurations in ^{24}Mg, similar to those predicted by Nilsson-Strutinsky and Cranked Alpha-Cluster Model calculations. If this interpretation is correct, the decay branch observed in the $^{12}C + ^{12}C$ inelastic scattering channel would correspond to the symmetric decay mode of this chain structure. It is likely, however, that different decay modes also exist for such a configuration. One such decay could be by the emission of a ^{8}Be nucleus, leaving ^{16}O in a highly excited state corresponding to the 4-alpha particle chain structure in that nucleus. These extended configurations in ^{16}O have been associated with resonances observed in the a + $^{12}C \rightarrow {}^{8}Be + {}^{8}Be$ reaction. As the chain structures in ^{16}O decay to 2 additional ^{8}Be nuclei, the resulting final state is then 3 ^{8}Be. Since ^{8}Be is unbound with respect to decay into 2 alpha particles, the ultimate final state is 6 alpha particles.

We performed a measurement to study in detail this and other reaction pathways that lead from $^{12}C + ^{12}C$ to 6 alpha particles. The experiment was carried out using an array of four double-sided silicon strip detectors (E.e.), placed at angles of 15 and 35 degrees on either side of the beam, at distances of 14 and 17 cm. The resulting solid angle covered by this array is approximately 430 msr, effectively divided into 1024 pixel regions. A ^{12}C beam from ATLAS bombarded 50-μg/cm^2 targets at 5 energies in the region of the structure in the $^{12}C + ^{12}C$ excitation function. All events with a measured particle fold of N = 3 or greater were recorded. From this data set, approximately 1,000 6-fold events, and 10,000 5-fold events were obtained at each energy. Under the assumption that for any event with more than four fragments in the final state, all particles are alpha particles, momentum reconstruction permits a complete characterization of the 6-body final state. The summed 6-alpha particle energy spectrum obtained at E_{lab} = 65 MeV appears in Fig. I-2.

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[1] 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, Phys. Rev. Lett. 68, 1295 (1992).

These data are still being analyzed. However, some preliminary results have been obtained. Events which appear to arise from the alpha-transfer reaction leading to $^{8}Be + ^{16}O$ (4a) have been tentatively identified (see Fig. I-3). The very large solid angle available also permits detailed study of reaction channels going through states at higher excitation energy in ^{12}C, e.g. the 3- level at 9.64 MeV. Prominent structures have also been observed in such reaction channels. By measuring the angular correlations between the alpha-particles from the decay of the 3- level, spin-alignment information can be obtained. Such data can provide important additional information about the reaction mechanisms leading to such final states in this system.

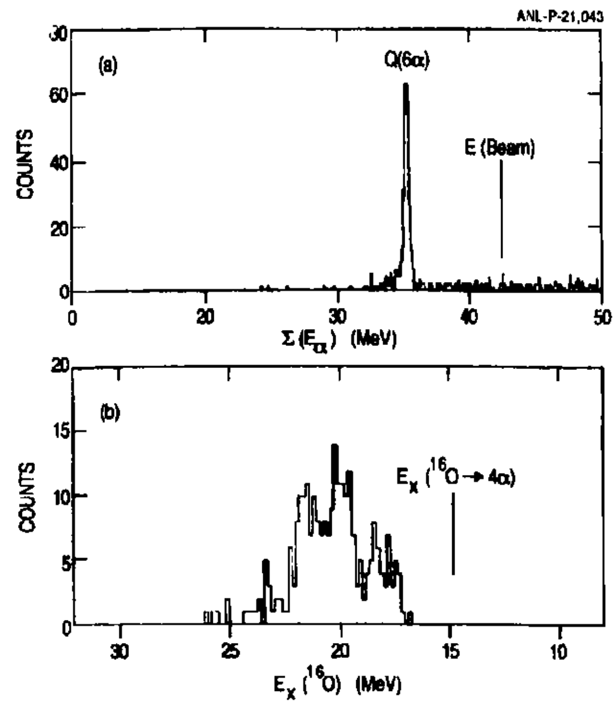

Fig. I-3. (a) Spectrum of total 6-alpha -particle sum energy obtained at E_{lab} = 65.0 MeV. The peak is at E_{lab} minus the separation energy for $^{12}C + ^{12}C \rightarrow$ 6 alpha. (b) Preliminary Q-value spectrum for the reaction $^{12}C(^{12}C,^{8}Be)^{16}O$ (4 aplha). The 4-alpha decay threshold is at $E_x(^{16}O)$ = 14.74 MeV.

b.3. Angular Distribution Measurements for $^{12}C + ^{12}C \rightarrow ^{12}C(0^+) + ^{12}C(0^+)$ Inelastic Scattering (A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, J. Gehring,* B. G. Glagola, T. Happ, D. J. Henderson, P. Wilt, and I. G. Bearden†)

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 A.b.1.). 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 with the theoretical expectations for linear alpha-particle structures in ^{24}Mg, we have obtained detailed inelastic

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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 E.e.) were used to detect the three alpha particles from the decay of one of the two excited 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 for 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 resulting angular distribution data obtained in this experiment covered from 20 to 105 degrees in the center-of-mass system for the $^{12}C(0^+)$+ $^{12}C(0^+)$ exit channel. Angular distribution data for 7 of the 8 energies studied appear in Fig. I-4.

A preliminary partial-wave analysis suggests a complicated interference between several angular momenta, with the dominant partial waves in the range of L = 14-16. This region of angular momentum is particularly interesting due to results of cranked alpha- cluster calculations for ^{24}Mg, which predict a crossing between rotational bands built upon ^{12}C - ^{12}C grazing trajectories and a 6 alpha-particle chain configuration to occur at
$E_x \sim 50$ MeV and L ~ 16 $\hbar$.

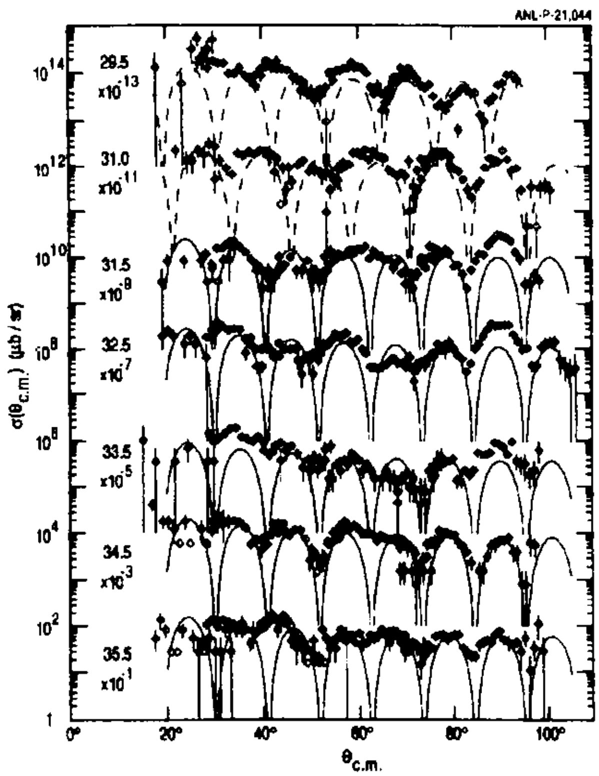

Fig. I-4. Angular-distribution data for $^{12}C+^{12}C \rightarrow ^{12}C(0^+)+^{12}C(0^+)$ mutual inelastic scattering. The solid (dashed) curves represent squared Legendre polynomials of degree 16 (14).

Another interesting comparison is suggested by Rae and Merchant, who calculate the $^{12}C + ^{12}C \rightarrow ^{12}C(0^+) + ^{12}C(0^+)$ angular distribution assuming a degenerate series of resonances, similar to what one would expect for a rotational band with an extremely large moment of inertia. Using this simple model, surprisingly good agreement is obtained for the present data.

b.4. Relationship between the Deformed Harmonic Oscillator and Clustering

(M. Freer, R. R. Betts, and A. H. Wuosmaa)

The role of clustering in nuclear structure is well established, and many models were developed which exploit this feature to predict spectral and structural properties of nuclei. The ^{24}Mg nucleus provided a fertile ground for such studies, where, for example, similarities between the forms of shape isomeric configurations predicted by both Nilsson-Strutinsky and alpha-cluster model calculations lead to the idea that clustering and deformation in this system might be intimately linked.

Calculations were performed which demonstrate that the cluster structures found in the alpha cluster model calculations, may be observed in the density profiles of the wavefunctions of the configurations found in the deformed shell-model calculations, thus providing a link between the two quite different models. Further, the relationship between the deformed shell model and the many-center shell model was explored in order to probe the symmetries in the deformed oscillator, and also to understand the decomposition of the shell-model configurations into their cluster components.

b.5. Search for Many-Body Decay of Resonances in the $^{24}Mg + ^{24}Mg$ System

(A. H. Wuosmaa, M. Freer, R. W. Zurmühle,* C. Lee,* S. P. Barrow,* Y. Miao,* N. Wimer,* B. R. Fulton,† and A. Murphy†)

Prominent resonance behavior has long been known to occur in systems involving nuclei in the s-d shell composed of integral numbers of alpha particles. One of the most striking examples of this behavior is found in the $^{24}Mg + ^{24}Mg$ system, where excitation functions reveal 3 groups of strong resonances at excitation energies between 60 and 70 MeV, with spins from 36 to 40 $\hbar$ in the composite system ^{48}Cr. These resonances were interpreted as arising from the population and subsequent binary decay of highly elongated configurations in the composite system ^{48}Cr. One puzzling feature of these resonances, however, is that only a small fraction, approximately 30%, of the total resonance strength is observed in the elastic and inelastic scattering channels for these peaks. The resonances have also been observed in alpha transfer reactions leading to the $^{20}Ne + ^{28}Si$ final state, but the resonance cross sections for these transfer reactions are far too small to explain the missing strength. One possibility is that these resonances possess large decay widths to particle unbound final states, e.g. a + $^{20}Ne + ^{24}Mg$, 2a + $^{20}Ne + ^{20}Ne$, etc. These final states are, in general, quite difficult to study with a conventional detector setup.

We used an experimental setup consisting of two highly segmented, large-area double-sided silicon strip detectors (DSSD's) combined with a large solid-angle gas ionization telescope to study many-body final states in the energy region of one strong resonance observed in the $^{24}Mg + ^{24}Mg$ system. A ^{24}Mg beam from the University of Pennsylvania tandem accelerator was used to bombard targets consisting of 30-μg/cm^2 ^{24}Mg evaporated on 15-μg/cm^2 ^{12}C backings at two energies, E_{cm} = 45.70 and 46.25, at the peak and off the

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peak, respectively, of one strong ^{24}Mg + ^{24}Mg elastic scattering resonance. Data were obtained for one week at each beam energy. Coincidences between any hit in either one or both of the DSSDs, and in the gas telescope were recorded in event mode. Particle identification was obtained from the relative time-of-flight information from the two DSSDs, as well as from the E-Δ E data in the gas telescope. Final states such as α + ^{20}Ne + ^{24}Mg have been identified. The analysis of these data is continuing at the University of Pennsylvania.

b.6. <u>^{20}Ne + ^{20}Ne Elastic and Inelastic Scattering</u> (M. Freer, A. H. Wuosmaa, R. R. Betts, S. Barrow,* Y. Miao,* J. T. Murgatroyd,* K. Pohl,* N. Wimer,* and R. W. Zurmühle*)

Resonances in elastic and inelastic scattering of light, near symmetric, nuclei, is a well documented phenomenon. Although the origin of the resonances is not completely understood, it is believed that they are associated with the formation of deformed configurations in the intermediate compound system. These resonance structures are particularly pronounced in target projectile systems composed of A = 4n nuclei. However, due to experimental difficulties in the study of the ^{20}Ne + ^{20}Ne reaction, there is little information available for this interesting system.

The development of the ECR source at ATLAS has facilitated the production of noble gas beams, and in conjunction with a ^{20}Ne target gas cell, constructed at the University on Pennsylvania, the first ^{20}Ne beam from ATLAS was employed to measure an excitation function, spanning beam energies from 70 to 83 MeV in 250-keV steps. Using the kinematic coincidence detection technique, the masses of the reaction products and the associated Q value were simultaneously determined. This allowed the resonance behavior of the elastic, several inelastic channels, and alpha transfer channels to be studied separately. The data are currently being analyzed.

*University of Pennsylvania

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 is on the study of superdeformation. Work at this laboratory provided first evidence for a new region of the periodic table where superdeformation occurs: the A ~ 190 region. First evidence was found in ^{191}Hg and considerable effort was focussed over the last four years on studying the properties of superdeformed nuclei in this region in great detail. The data observed from these superdeformation studies are of such high statistical accuracy that they provide excellent opportunities to perform investigations of other structure phenomena in the nuclei of interest. In particular, such detailed studies allow objective (b) outlined above to be addressed.

Most projects described in this section took 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 ΔE-E or time-of-flight techniques is also available. This equipment has been constructed by the University of Kansas group. 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.). Support for up to 7 Compton-suppressed spectrometers at the magnetic spectrograph is also available. Ten of the Compton-suppressed spectrometers can also be located at the target position of the Fragment Mass Analyzer (FMA). A special scattering chamber for use of the γ-ray detectors at the FMA is available as well as a dedicated electronics set-up.

New large gamma-ray detector arrays are currently under construction in the U.S. (GAMMASPHERE) and in Europe (EUROGAM). These new arrays provide new opportunities for nuclear structure research. Argonne is participating vigorously in the construction of GAMMASPHERE and will perform first experiments with the so-called "early implementation phase" of the device in 1993. The group also collaborated in two experiments at EUROGAM.

Several projects are joint efforts with outside user groups from the University of Notre Dame, Purdue University, INEL-Idaho Engineering Lab., the University of Manchester, Rutgers University, the University of Tennessee, Tennessee Technological University, and Yale University. The work at EUROGAM was performed in collaboration with several other European laboratories.

A. Superdeformed Nuclei

Following calculations by R. Chasman, we reported four years ago on evidence for the existence of a new region of superdeformation around ^{192}Hg. ATLAS work found superdeformed bands in a chain of Hg nuclei with A = 189-192, and in ^{193}Tl. More recently, superdeformed bands were also investigated in ^{192,195,196}Pb and ^{191,192}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 detected efficiently, 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 was first 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 $\hbar\omega$. Lifetime measurements of individual members of the superdeformed band in ^{192}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, which are successful in reproducing the data, attribute the rise in $J^{(2)}$ to the alignment of a pair of protons and neutrons, both occupying high-N intruder orbitals. Experiments performed last year provide strong support for the calculations and, at the same time, highlight their limits. Six superdeformed bands were found in the odd-odd ^{192}Tl nucleus. For two of the bands, $J^{(2)}$ was found to be constant with $\hbar\omega$. This result can be understood in terms of Fermi blocking of quasiparticle alignments in the high-N intruder orbitals and represents the first strong experimental evidence for this alignment picture.

Another experimental indication in favor of this alignment picture was provided by the evolution of $J^{(2)}$ in the ^{190}Hg and ^{196}Pb nuclei. In both cases, a distinct change in the slope of the dynamic moment of inertia $J^{(2)}$ vs $\hbar\omega$ is observed at the highest frequencies ($\hbar\omega \geq 0.35$ MeV). This result is interpreted as evidence for a band interaction at the highest frequencies, analogous to the band interaction responsible for the backbending phenomenon seen at moderate deformation in many rare-earth nuclei. However, the cranked shell-model calculations are unable to calculate the crossing frequency and the interaction strength correctly. At present, there is no satisfactory explanation for these failures. Possible roles of a strong residual neutron-proton interaction and/or of higher order corrections to the pairing field are currently being investigated by several theorists.

Questions concerning the properties associated with the feeding and the decay of the superdeformed bands near A = 190 were also addressed. Superdeformation occurs because of the presence 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 were 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. Very recently, we participated in an experiment on ^{192}Hg at EUROGAM from which we hope to isolate the spectrum of the γ rays feeding the SD band as well as the spectrum of the decay γ rays.

We developed a model to follow the history of SD bands from formation to decay. The model accounts successfully for the SD entry distributions, the population intensities of SD bands and the variation of intensities with spin. Calculations of the decay can explain 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 EUROGAM data should allow us to test these calculations further.

a.1. Double Blocking in the ^{192}Tl Superdeformed Nucleus (Y. Liang, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, R. G. Henry, T. L. Khoo, T. Lauritsen, F. Soramel,* S. Pilotte,† J. M. Lewis,‡ L. L. Riedinger,‡ C.-H. Yu,‡ U. Garg,§ W. Reviol,§ and I. G. Bearden¶)

One of the most intriguing differences between the properties of superdeformed (SD) nuclei in the A = 150 and A = 190 regions is the behavior of the dynamic moments of inertia $J^{(2)}$ as a function of the rotational frequency $\hbar\omega$. The pronounced isotopic and isotonic variations of $J^{(2)}$ with $\hbar\omega$ seen in the SD bands near A = 150 have been attributed to a large extent to differences in the occupation of specific high-N intruder orbitals. In contrast, the vast majority of SD bands near A = 190 displays the same smooth, pronounced increase of $J^{(2)}$ with $\hbar\omega$. It has been shown that the occupation of specific high-N intruders cannot account for this observed rise. An explanation in terms of changes in deformation with $\hbar\omega$ has also been ruled out from lifetime measurements performed at Argonne[1] and discussed in earlier reports. It has been suggested that quasiparticle alignments and the resulting changes in pairing play an essential role. Experimental evidence for this alignment picture is at present circumstantial. Small differences in the absolute value and the rate of increase of $J^{(2)}$ with $\hbar\omega$ were noted when comparing even-even nuclei with the odd-even neighbors and have been interpreted in terms of the blocking of either the proton or the neutron alignment in the odd-even neighbor. Clearly, the study of the behavior of $J^{(2)}$ in the SD bands of an odd-odd nucleus should be particularly revealing. If both the odd proton and the odd neutron occupy the high-N intruder orbitals, the alignments should be blocked and, as a result, the moments of inertia should be constant with frequency. In order to elucidate this question further a study of the odd-odd nucleus ^{192}Tl was undertaken. The states in ^{192}Tl were populated with the ^{160}Gd(^{37}Cl,5n) reaction at beam energies of 178 and 181 MeV. The target consisted of a stack of two isotopically enriched self-supporting 500-μg/cm^2 thick foils. The γ rays of interest were detected using the Argonne- Notre Dame BGO γ-ray facility. With a threshold of four on the number of array elements firing in coincidence with at least two Compton-suppressed Ge detectors, a total of ~10^8 events were collected event-by-event at each beam energy. The detailed analysis revealed the presence of six rotational bands (Fig. I-5) with average energy differences between consecutive transitions

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[1]E. F. Moore et al., Phys. Rev . Lett. 64, 3127 (1990).

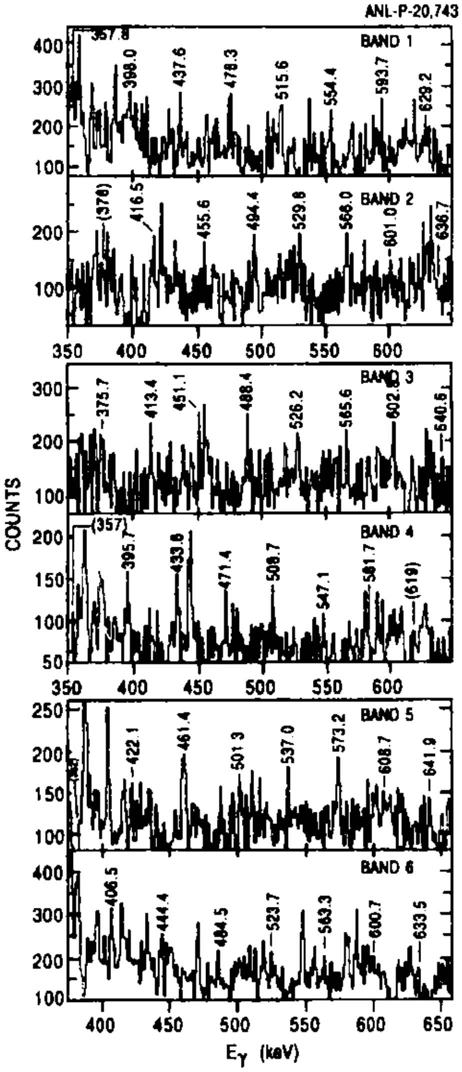

Fig. I-5. γ-ray spectra obtained for the six SD bands n ^{192}Tl by summing coincidence gates. The SDband energies are indicated. Transitions for which the placement is not certain are given under parentheses. The intensity in the SD bands is small and several contaminants are also present in the spectra. The spectra are grouped into pairs according to the interpretation of the bands as signa ure partners.

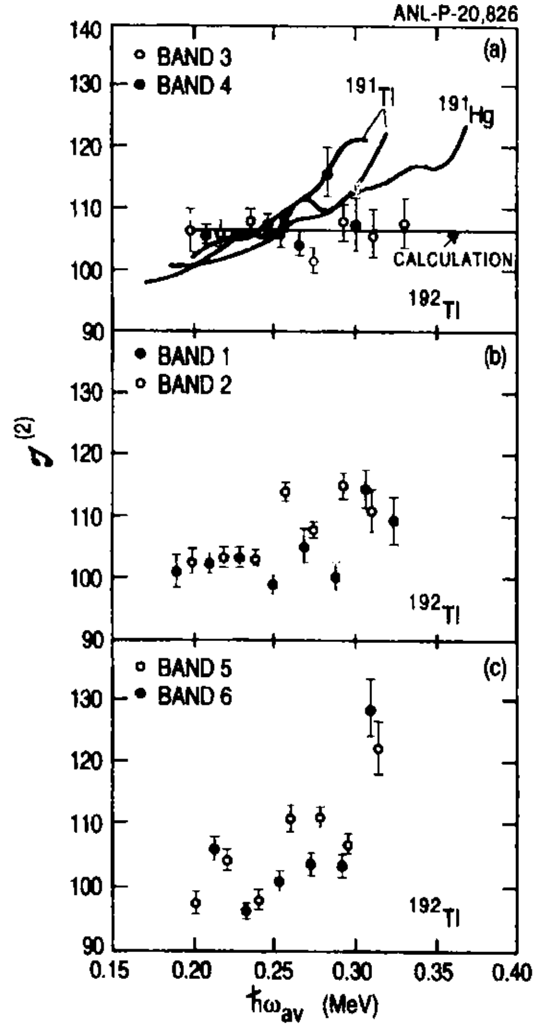

Fig. I-6. Dynamic moments of inertia $J^{(2)}$ f or the six SD bands in ^{192}Tl. (a): the $J^{(2)}$ values for bands 3 and 4 are compared with those of the two SD bands in ^{191}Tl and with the first SD band in ^{191}Hg (thick l ines). The result of cranking calculations discussed in the text is given as the thin ilne. (b) and (c): dynamic moments of inertia for bands 1 & 2, and 5 & 5, respectively.

of ~38 keV, the spacing expected for a SD shape. In analogy with the neighboring ^{191,193,194}Tl isotopes, bands appear in pairs that can be interpreted as signature partners. The dependence of the dynamic moments of inertia for the six bands as a function of the rotational frequency exhibits the following features (Fig. I-6): (i) $J^{(2)}$ remains constant with $\hbar\omega$ for two of the bands (labelled bands 3 and 4 hereafter) while (ii) it displays the more typical rise with $\hbar\omega$ for the other four SD bands (labelled bands 1, 2, 5 and 6). These data represent the first case where constant values of $J^{(2)}$ have been observed in SD bands near A = 190. A comparison between the $J^{(2)}$ values for bands 3 and 4 and (a) those of the odd-even neighboring nuclei ^{191}Hg and ^{191}Tl and (b) those seen in bands 1-2, 5-6 indicates that, at the lowest frequencies, the value of $J^{(2)}$ is higher in bands 3-4.

We performed cranking calculations with the Warsaw Wood-Saxon code to calculate quasiparticle Routhians and $J^{(2)}$ values for the superdeformed ^{192}Tl nucleus and its neighbors. While specific results depend on the deformation and the pairing gaps used, the following general conclusions can be drawn. (i) An alignment of a N = 7 neutron pair, which is calculated to occur in ^{191}Tl (and ^{192}Hg) within $0.15 \leq \hbar\omega \leq 0.3$ MeV, is blocked in ^{192}Tl (and ^{191}Hg) when the odd neutron occupies a $j_{15/2}$ orbital involved. (ii) An alignment of a pair of N = 6 protons is calculated to occur between $0.25 \leq \hbar\omega \leq 0.4$ MeV in ^{191}Hg (and ^{192}Hg). This alignment is also blocked in ^{192}Tl (and ^{191}Tl) when the proton occupies an $i_{13/2}$ orbital. (iii) at low values of $\hbar\omega$, our calculations show that the occupation of both the $\pi i_{13/2}$ and $\nu j_{15/2}$ orbitals will result in an additional contribution to $J^{(2)}$ with respect to the odd-even neighboring nuclei. The calculated $J^{(2)}$ value for this double-intruder configuration, agrees well with the data. On the basis of this discussion, we propose that bands 3 and 4 correspond to a configuration built on the favored (r = +i) signature of the $\nu j_{15/2}$ orbital coupled to the two signatures (r = ± i) of the $\pi i_{13/2}$ orbital. The same calculations together with comparisons with the neighboring SD nuclei also allow the proposal of configurations for the other four bands. We propose that the four bands are associated with the intruder $\pi(i_{13/2})^5$ proton configuration coupled to the lowest neutron excitation identified in ^{191}Hg, i.e. the ν[642]3/2 orbital. It is worth pointing out that a similar classification can be proposed for the six SD bands in ^{194}Tl observed some time ago at LBL.[2] A paper reporting these results has been published recently.[3]

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[2]F. Azaiez, Phys. Rev. Lett. 66, 1030 (1991), [3]Y. Liang, Phys. Rev. C 46, R2136 (1992).

a.2. Higher Superdeformed Band Members in ^{190}Hg: Evidence for a Band Interaction? (R. V. F. Janssens, M. P. Carpenter, I. Ahmad, T. L. Khoo, T. Lauritsen, I. G. Bearden,* P. J. Daly,† M. W. Drigert,‡ U. Garg,§ W. Reviol,§ and R. Wyss¶)

We reported last year on a new investigation of ^{192}Hg, in which it was possible to extend the superdeformed (SD) band to higher frequencies than previously known.[1] The main result of this investigation is that $J^{(2)}$, the dynamic moment of inertia, keeps rising with the rotational frequency $\hbar\omega$ over the entire frequency range. This result is surprising as all available cranking calculations predict a downturn of $J^{(2)}$ in the observed frequency range. It is a direct consequence of this type of calculation that, after the quasiparticle

alignments (which are thought to be responsible for the rise in $J^{(2)}$) have taken place, $J^{(2)}$ will exhibit a downturn with increasing $\hbar\omega$ and will approach the value of the static moment of inertia $J^{(1)}$. Thus, the data at high rotational frequencies lead one to question the validity of the physical interpretation on which the calculations are based. In order to assess whether this result is unique, we reanalyzed a large coincidence data set for ^{190}Hg.

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*Resident Graduate Student from Purdue University, †Purdue University, ‡Idaho National Engineering Laboratory, §University of Notre Dame, ¶Joint Institute for Heavy-Ion Research, Oak Ridge National Laboratory, [1]T. Lauritsen et al., Phys. Lett. B279, 239 (1992).

Coincidence data obtained in previous years with the $^{160}Gd(^{34}S,4n)$ reaction at three beam energies (159, 162, 165 MeV) were used. In the analysis, a coincidence matrix was constructed where events corresponding to high- multiplicity cascades in ^{190}Hg were enhanced by careful selection of conditions on the γ-ray multiplicity and on total energy recorded in the inner array of the Argonne Notre Dame BGO γ-ray facility. These conditions were adjusted at each beam energy, in order to reflect corresponding changes in input angular momentum and excitation energy. From the analysis of the coincidence matrix we were able to add three new γ rays on top of the SD band.

With the addition of these new transitions a surprising new result is obtained for the behavior of $J^{(2)}$ vs $\hbar\omega$: two markedly different slopes in $J^{(2)}$ are present (Fig. I-7). At frequencies $\hbar\omega \leq 0.32$ MeV, there is a smooth rise with a slope similar to that of ^{192}Hg, while for the higher frequencies, a clear upbend in the data points is observed. Such a change in slope is very similar to those seen in many rotational bands at normal deformation and strongly suggests the presence of a crossing between the SD "ground-state" band and another band.

We performed CSM calculations in order to try to understand the results. The parameters for the latter (pairing, deformations etc.) were those used in our earlier calculations for $^{190,192}Hg$. These calculations predict a sharp rise in the moment of inertia brought about mainly by the relatively weak interaction strength (~100 keV, in contrast the corresponding

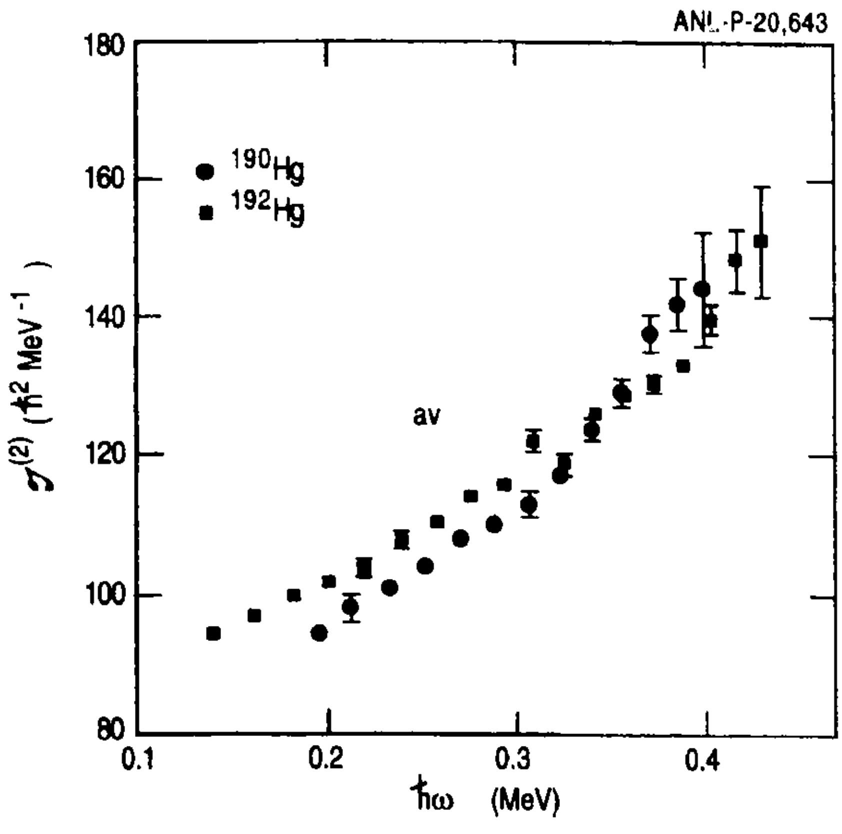

Fig. I-7. Dynamic moments of inertia $J^{(2)}$ vs $\hbar\omega$ for the latest data sets on the SD bands in ^{190}Hg and ^{192}Hg.

strength in ^{192,194}Hg is ~500 keV) between the ground-state and the aligned $j_{15/2}$ neutron SD band. This sharp rise is not present in the data. The comparison between data and calculations then suggests that the alignment process is (1) delayed in frequency and (2) occurs with a larger interaction strength than the calculations predict. There is at present no satisfactory explanation for these observations. However, the possibility that higher-order corrections to the pairing (configuration dependent pairing) will be required in order to bring CSM predictions in agreement with the data are currently being explored. This project is part of the thesis of I. G. Bearden.

a.3. <u>Superdeformation Studies in ^{195,196}Pb</u> (Y. Liang, R. V. F. Janssens, M. P. Carpenter, I. Ahmad, R. G. Henry, T. L. Khoo, T. Lauritsen, W. Reviol,* U. Garg,* I. G. Bearden,† P. J. Daly,* B. Fornal,‡ R. Mayer,‡ M. W. Drigert,§ and F. Soramel¶)

The study of superdeformation (SD) in the Pb isotopes has been undertaken with the following general motivations: (1) Calculations for the Pb nuclei show rather strong octupole effects for which experimental evidence is currently at best rather weak; (2) finding excited SD 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, and (3) the possible discovery of so-called "identical" SD 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 used the ^{170}Er(^{30}Si, 4n and 5n) reactions to study the nuclei ^{196,195}Pb with ATLAS beams of 142, 146 and 155 MeV. At this stage in the analysis the following conclusions can be drawn: (1) A SD band reported earlier by Brinkmann et al.[1] is observed in our data. One transition was added at the bottom of the band, three other γ rays were added to the high-energy end of the spectrum. (2) Our preliminary analysis reported last year lead us to question, to some degree, the isotopic assignment of this band to ^{196}Pb. This issue has been resolved by a careful investigation of the data at the lowest beam energy and the assignment of this SD band to ^{196}Pb is now certain. (3) No other SD bands could be found in either ^{196}Pb or ^{195}Pb.

The dynamic moment of inertia $J^{(2)}$ of this SD band exhibits a behavior as a function of rotational frequency $\hbar\omega$ which is similar to that first observed in ^{190}Hg (see preceding contribution to this report); i.e. a change in the slope of the curve for $\hbar\omega > 0.3$ MeV is present. This result suggests that an interaction with another SD band with larger initial alignment occurs in this frequency range. Cranked shell-model calculations are unable to reproduce this phenomenon and, as in the case of ^{190}Hg, corrections to the calculations for higher- order effects in the pairing are currently being explored. An experiment aiming at the measurements of the lifetimes of the SD states with the Doppler-shift attenuation method is schedulec to run early in 1993. The results obtained thus far are being written up for publication.

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[1]M. J. Brinkmann et al., Z. Phys. <u>A336</u>, 115 (1990).

a.4. Lack of Evidence for a Superdeformed Band in ^{192}Pb (R. V. F. Janssens, I. Ahmad, M. P. Carpenter, T. L. Khoo, T. Lauritsen, Y. Liang, A. J. M. Plompen,* M. N. Harakeh,* W. H. A. Hesseling,* G. Van't Hof,* N. Kalentar-Nayestanaki,* J. P. S. van Schagen,* U. Garg,† W. Reviol,† D. Ye,† and I. G. Bearden‡)

The Livermore-Berkeley collaboration recently reported a superdeformed (SD) band of nine transitions in the ^{192}Pb nucleus.[1] This result appeared somewhat surprising as cranked Strutinsky calculations by Chasman[2] and Nazarewicz et al.[3] 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.

The ^{173}Yb(^{24}Mg, 5n) reaction at a beam energy of 132 MeV was used 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 Pb backing. Thus, the recoiling nuclei decay while slowing down in the Pb 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. To our surprise, no sequence of transitions could be identified that can be associated with the reported SD band. While some of the reported transitions seem to be present in some of the coincidence spectra, none of them appears consistently in all spectra. When transitions are present they can usually be understood as resulting from coincidence relationships expected from contaminant transitions in ^{190}Hg and/or ^{192}Pb. When present, the reported transitions appear to have energies corresponding to emission from stopped nuclei and no evidence for Doppler-broadened lineshapes could be found. All spectra contain numerous other peaks, which again can be understood on the basis of the coincidence relationships expected from known contaminants belonging mainly to ^{190}Hg, a nucleus produced with large intensity in the reaction. It must therefore be concluded that the presence of the reported SD band in ^{192}Pb cannot be confirmed from the present analysis.

This experiment is part of the thesis of A. J. M. Plompen. A brief report summarizing the present findings was submitted for publication.

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*Free University, Amsterdam, The Netherlands, †University of Notre Dame, ‡Resident Graduate Student from Purdue University, [1]E. A. Henry et al., Z. Phys. A338, 469 (1991), [2]R. R. Chasman, Phys. Lett. B219, 227 (1989), [3]W. Satula, et al., Nucl. Phys. A529, 289 (1991).

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 were observed recently in the Tl ($Z = 81$) isotopes $^{192-195}$Tl. From the current results on superdeformation in Hg nuclei, it appears that the superdeformation region ends for $Z = 80$ at $N = 108$. It is also observed that the superdeformed bands seen in the Tl isotopes are more weakly populated than their isotonic

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*University of Ottawa, Canada, †University of Tennessee, ‡Resident Graduate Student from Purdue University, [1]M. W. Drigert et al., Nucl. Phys. A530, 452 (1991).

neighbors in the Hg nuclei. Thus a question arose concerning whether the Tl superdeformed chain extends as low in neutron number as for the Hg isotopes.

In an attempt to address this question, two experiments were performed at the Holifield Heavy Ion Facility at Oak Ridge National Laboratory to search for evidence of superdeformation in ^{191}Tl (a superdeformed band has already been observed for the isotone of this nucleus ^{190}Hg).[1] The first experiment utilized the ^{159}Tb(^{36}S,4n) reaction at 165 MeV in order to populate excited states in ^{191}Tl, and γ-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 at the Holifield facility 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.

In an attempt to confirm the presence of the proposed SD band, an experiment was performed at ATLAS on ^{191}Tl using the Argonne-Notre Dame BGO γ-ray facility. High-spin states in ^{191}Tl were populated using the ^{159}Tb(^{36}S,4n) reaction at 165 MeV. Two γ-ray sequences consisting of 8 and 10 transitions with an average spacing between consecutive γ rays of 38 keV were identified in the data analysis (see Fig. I-8). The intensity of these transitions was estimated to represent ~ 0.4% of all 4n reaction products. The characteristics of these two bands agree well with what is observed in other SD bands identified in this mass region. First, the dynamical moment of inertia for both bands rises with increasing $\hbar\omega$. Secondly, the two bands appear to be signature partners built on the same intrinsic configuration. Evidence for this comes from the fact that over a wide energy range, the energy of a γ ray in one of the two bands lies almost exactly midway between the energies of two consecutive transitions in the other band (see Fig. I-8). A similar relationship between SD bands is observed in ^{193}Tl and ^{195}Tl and is consistent with the suggested intrinsic configuration of $\pi i_{13/2}$ [642]5/2$^+$ for these bands. Thus, the same configuration is proposed for the two SD bands in ^{191}Tl. This new data also extends the A ~ 190 island of superdeformation to N = 110 in the Tl isotopes. A paper is being prepared for publication.

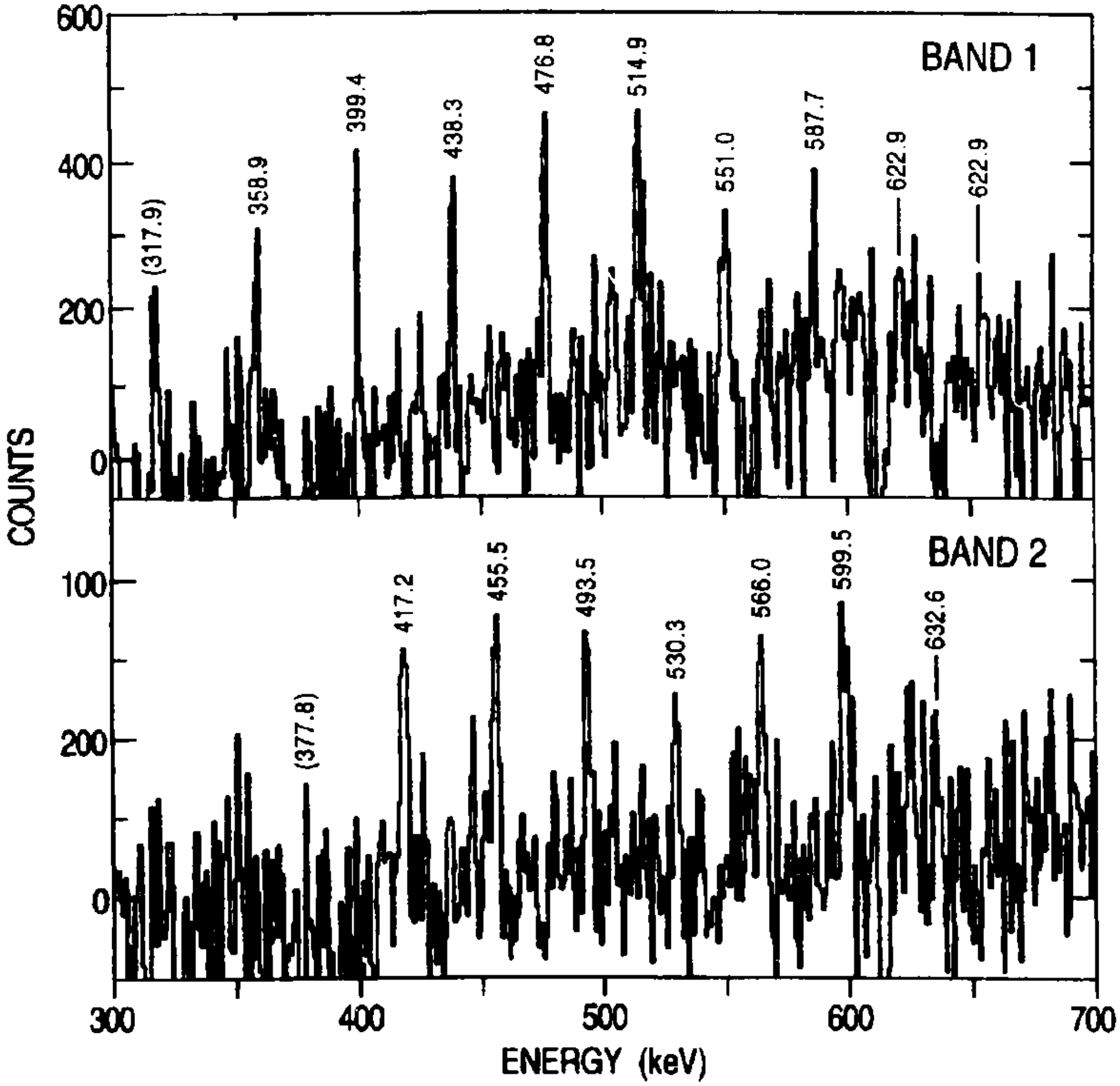

Fig. 1-8. Efficiency corrected γ-ray spectra for the two SD bands in ^{191}Tl. Transitions for which the placement is uncertain are given in parentheses.

a.6. Feeding of Superdeformed Bands: the Mechanism and Constraints on Band Energies and the Well Depth (T. Lauritsen, T. L. Khoo, I. Ahmad, M. P. Carpenter, P. Fernandez, R. V. F. Janssens, E. F. Moore, F. L. H. Wolfs, P. Benet,* P. J. Daly,* K. B. Beard,† D. Ye,† U. Garg,† and M. W. Drigert‡)

Superdeformed bands are built on the ground state or low-lying excitations in a secondary minimum, or false vacuum. Thus, the feeding of SD bands is a process where the compound nucleus is trapped in a false vacuum. We have studied the feeding both through experiment and calculation. We are able to account for the surprisingly large SD intensity and the portion of the initial states (characterized in terms of energy and spin) which result in trapping in the false vacuum. Furthermore, we are able to place constraints on the SD band energy and the barrier height separating the normal and SD states. The results of this study have been published.[1]

We 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}S, 4n) reaction. (H refers to the sum energy and k the number of detectors which fire, before correction for the instrumental response).

The (H,k) distributions were 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). These distributions are given in Fig. I-8. 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. 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 reproduce successfully all the observables connected with feeding of SD bands, including the entry distribution, and the SD band intensity (and variation of intensity) with spin (see Fig. I-9). It 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.

Comparisons of the experimental and calculated intensities and entry distributions allow one to place rather tight constraints on the energy 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 in the A = 150 and 190 regions, although over 50 SD bands have been detected At the point of the decay, we propose that the SD band lies 3.3 - 4.3 MeV above the normal yrast line. The well depth at spin 40, the average value we are sensitive to in the feeding process, is 3.5 - 4.5 MeV.

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*Purdue University, †University of Notre Dame, ‡Idaho National Engineering Laboratory,
[1]T. Lauritsen et al., Phys. Rev. Lett. 69, 2479 (1992).

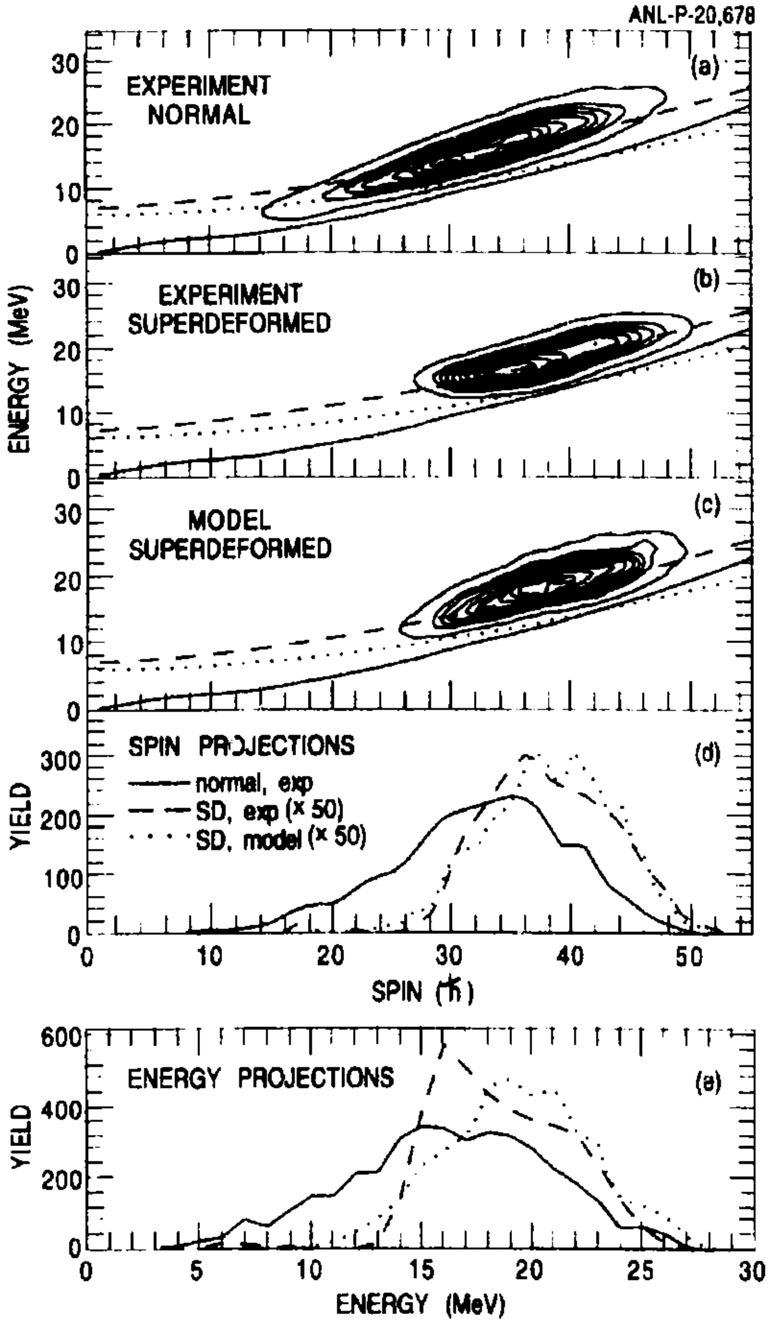

Fig. I-9. Measured entry distributions leading to the population of (a) normal and (b) SD states in ^{192}Hg; contours represent changes of 10% of the maximum value. (c) Calculated entry distribution for SD states. (d) and (e) show the projections on the spin and energy axes, respectively, for the measured and calculated entry distributions; the SD distributions are multiplied by 50. Also shown in Fig. a-c are the normal (solid line) and SD (dots) yrast lines, and the barrier separating the two classes of states (dash). The SD band and barrier shown here give the best overall agreement between calculation and experiment.

a.7. Calculations of the Decay Out 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 the SD bands into the normal states has not been well understood. Following Vigezzi et al.[1], 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 that 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 decreases rapidly at low spin since the rate scales as E_γ^5 and the fractional decrease of E_γ is large at low spin.

We developed a model 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 Γ of the SD state among the sea of normal states turns out to be surprisingly small; for the A = 190 region it is a few percent of the average spacing between normal states. The matrix element coupling SD and normal states is around 30 eV. 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 can be inferred from the empirically deduced values of Γ (with some assumptions) and gives W = 0.5-1.3 MeV in the A = 190 region, when the SD bands decay at spins of ~ 10 $\hbar$. At spin 40, W is between 3.5 and 4.5 MeV (see B.a.6). Thus, we have the first experimental indications that W increases with spin. Furthermore, the sudden decay as a function of spin can only be obtained using a barrier which increases with spin.

The tunnelling is actually governed by the barrier curvature, or by the action, which is related to the area under the barrier. The derived action is 3 - 7 $\hbar$. Calculations by Shimizu et al.[2] give a value of 3.5 $\hbar$.

[1]E. Vigezzi et al., Phys. Lett. B249, 163 (1990).
[2]Y. R. Shimizu et al., Phys. Lett. B274, 243 (1992).

a.8. Gamma Rays Feeding and Depopulating SD States in ^{192}Hg (T. Lauritsen, T. L. Khoo, E. F. Moore, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, Y. Liang, M. Freer, A. Wuosmaa, P. Fernandez, P. Benet,* I. Bearden,† P. J. Daly,* B. Fornal,* 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 B.a.7 ascribes the decay out of the SD band to mixing with the normal states in which it is embedded. Thus, the spectrum of decay γ rays is simply that from an excited normal state, with excitation energy above yrast of ~ 3-5 MeV. We calculated this spectrum and, as expected, it shows a statistical distribution.

We are attempting to isolate the corresponding experimental spectrum of γ rays which populate and depopulate SD bands. The approach is to measure the total γ spectrum

*Purdue University, †Resident Graduate Student from Purdue University, ‡University of Notre Dame coincident with SD band transitions in Ge detectors. The major task is to disentangle these γ 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 γ spectra show these very features. There is an additional component located mainly below 0.6 MeV, which likely arises from decay out of the SD band. The limited statistics do not allow a reliable extraction of the spectrum of this component. However, we have significantly more data from the EUROGAM experiment which will be used for this purpose (see B.a.9).

a.9. ^{192}Hg EUROGAM Experiment (T. Lauritsen, R. G. Henry, T. L. Khoo, M. P. Carpenter, I. Ahmad, I. G. Bearden,* R. V. F. Janssens, Y. Liang, F. Hannachi,† I. Deloncle,† B. Gall,† M. G. Porquet,† C. Schuck,† G. Smith,† R. Beraud,‡ Y. Lecoz,‡ M. Meyer,‡ N. Redon,‡ F. Azaiez,§ C. Bourgeois,§ J. Duprat,§ A. Korichi,§ N. Perrin,§ H. Sergolle,§ H. Hubel,¶ P. Willsau,¶ J. Sharpey-Schafer,# C. Beausang,# E. Paul,# M. Joyce,# B. Wadsworth,** R. Clark,** and J. Simpson††)

A new generation of very large gamma-ray detector arrays are now either in operation or under construction. The EUROGAM array built by a French-English collaboration has, in its early implementation (at the Daresbury Laboratory, U.K.), a total of 43 Compton-suppressed detectors available out of the 71 in the final version.

We collaborated with French and English nuclear spectroscopy groups in an experiment to study the superdeformed band in ^{192}Hg, a nucleus that was studied in great detail at ANL.[1]

We used a beam of 159-MeV ^{36}S from the Daresbury tandem accelerator impinging on both a backed and an unbacked target of ^{160}Gd. We obtained high-fold data which will enable us to investigate the SD band in much greater detail than was previously possible. Among other things, we plan to apply a method (suggested by B. Herskind) of summing gamma rays in coincidence with the SD band in order to determine the excitation energy and spin of the SD band. In the decay out from the SD well the initial and final states have fixed energies; but the intermediate states will, due to a high level density, be distributed and thus the usual gamma spectrum will be a distribution rather than a sharp line. However, the sums of the gamma rays should show a sharp peak.

In addition, work is in progress to analyze the quasicontinuum of gamma rays in coincidence with the SD band and normal bands of the nucleus in a manner described in section B.a.8. We will generate the response function of the array using gamma spectra obtained from single and double line sources. The response function will be used to unfold the gamma spectra.

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*Resident Graduate Student from Purdue University, †Centre de Spectrometrie Nucleaire et de Spectrometrie de Masse, Orsay, France, ‡Universite Claude Bernard, Lyon, France, §Institut de Physique Nucleaire, Orsay, France, ¶Universität Bonn, Germany, #University of Liverpool, United Kingdom, **University of York, United Kingdom, ††SERC, Daresbury Laboratory, United Kingdom, [1]See for example R.V.F. Janssens et al., Nucl. Phys. A520, 75C (1990).

a.10. Entrance-Channel Dependence in the Population of the Superdeformed Bands in ^{192}Hg (F. Soramel, T. L. Khoo, R. V. F. Janssens, I. Ahmad, M. P. Carpenter, T. Lauritsen, Y. Liang, B. Fornal,* I. Bearden,† Ph. Benet,* P. J. Daly,* Z. W Grabowski,* R. Maier,* D. Ye,‡ U. Garg,‡ W. Reviol,‡ and M. W. Drigert§)

Recent data from Chalk River and Daresbury suggest that the population intensities of SD bands in ^{147}Gd and ^{152}Dy depend on the entrance channel used to produce the SD bands.[1,2] For example, the SD band intensities in ^{152}Dy are ~ 1% and 2% of the ground-state population in the ^{120}Sn(^{36}S,4n)^{152}Dy and ^{74}Ge(^{82}Se,4n)^{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 ℓ-distribution for the mass-symmetric entrance channel. One way to ensure similar ℓ-distributions is to have fission impose the dominant cut-off in the high-ℓ tail of the distribution. This can be achieved in the A = 190 region, where fission dominates beyond ~ 40$\hbar$.

We measured the entrance-channel dependence of the intensity of the SD bands in ^{191}Hg using the ^{130}Te(^{64}Ni,3n) and ^{160}Gd(^{36}S,5n)^{191}Hg reactions at mid-target bombarding energies of 259 and 169 MeV, where ℓ_{max} for both reactions is ~ 50$\hbar$, 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. This is shown in Fig. I-10(a) where the intensities measured in the two reactions are compared. 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 do emphasize that other effects than the entrance channel must also be considered. In particular, the SD intensity is extremely sensitive to the ℓ distribution, since it originates mainly from the higher partial waves. For both reactions, the sum-energy and spin distributions for ^{191}Hg have been measured [Fig. I-10(b)] and found to be very similar, although the spin distribution in the Ni-induced reaction is slightly lower (by 1 $\hbar$), which may account for the smaller intensity of the SD band in this reaction. These distributions also need to be measured for the reactions in the A = 150 region before a convincing case can be made that SD intensity differences are governed only by the entrance channel. The analysis for ^{191}Hg is now complete and a paper will be prepared.

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*Purdue University, †Resident Graduate Student from Purdue University, ‡University of Notre Dame, §Idaho National Engineering Laboratory, [1]G. Smith et al., Phys. Rev. Lett. 68, 158 (1992), [2]S. Flibotte et al., Phys. Rev. C 45, R889 (1992).

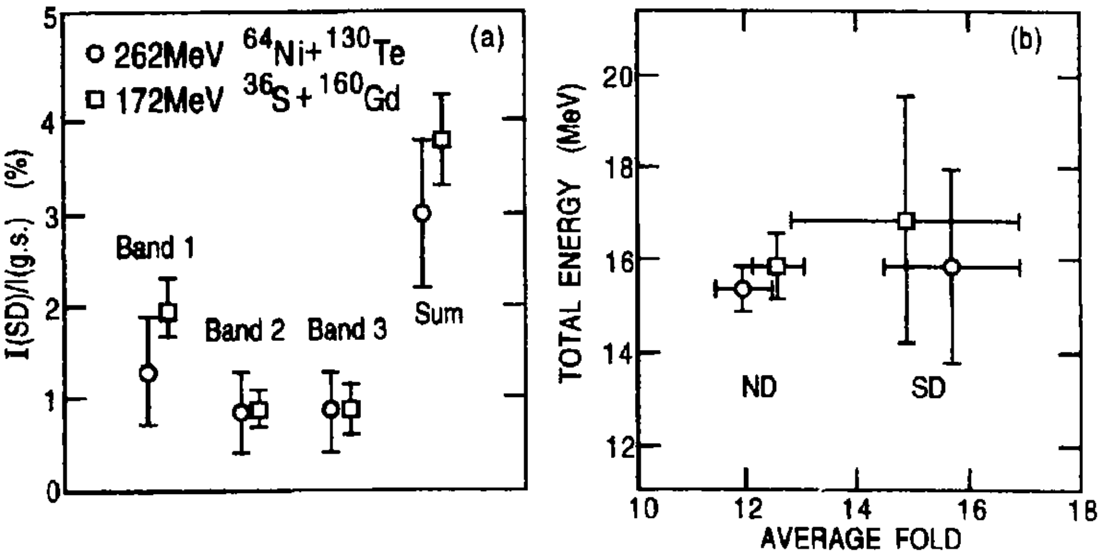

Fig. I-10. (a) Relative intensities of each SD band and total SD flux in ^{191}Hg for different reactions. (b) Experimental entry points for ND and SD states.

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 concentrated mainly on nuclei in the A ~ 190 region, where most of the superdeformation studies were 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 (γ = -60°, in the Lund convention). Our studies concentrated on the yrast and near-yrast structures of the $^{188-191}$Hg isotopes, which involve mainly neutron excitations, and on proton excitations in ^{192,195,196}Pb. So-called M1 bands were identified in the Pb isotopes. Bands of this type were the subject of extensive studies at several laboratories. In most cases, it has so far not been possible to establish the spins and excitation energies associated with these band structures because of the highly fragmented nature of their decay towards known yrast states. In ^{192}Pb and ^{196}Pb, were able to delineate the γ decay for some of the structures and, as a result, it was possible to propose quasiparticle configurations responsible for this new type of oblate collective rotation.

The Argonne Fragment Mass Analyzer (FMA) is now in operation and can be used in conjunction with 10 Compton Suppressed Ge detectors for studies of changes in nuclear structure as a function of proton and neutron number by moving further away from the line of stability. During the year, first experiments with the FMA were performed.

We showed in earlier years that nuclear structure investigations in neutron-rich nuclei can be performed successfully in studies of prompt gamma radiation from fission sources. The Argonne group participated in an experiment at EUROGAM where triple and higher- fold coincidence events from a ^{248}Cm source were recorded.

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 around A = 100 (Ru isotopes) (2) the study of the low spin structure of Po nuclei, (3) the study of the decay of high-K isomers in ^{176}W, and (4) the study of quasi-particle excitations in neutron-rich Sn nuclei.

b.1. **Yrast and Near-Yrast Spectroscopy in $^{188-190}$Hg** (R. V. F. Janssens, M. P. Carpenter, I. Ahmad, T. L. Khoo, T. Lauritsen, I. G. Bearden,* P. J. Daly,† Z. W. Grabowski,† B. Fornal,† R. M. Mayer,† U. Garg,‡ W. Reviol,‡ and M. W. Drigert§)

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 ^{188,189,190}Hg where such investigations were carried out at ATLAS over the last three years. With the ^{156}Gd(^{36}S,4n)^{188}Hg reaction at 167 MeV and ^{160}Gd(^{34}S,4n or 5n) ^{190,189}Hg reactions at 159, 162 and 165 MeV, large γ-γ coincidence data sets were obtained both with a stack of two 500-μg/cm^2 self-supporting targets and with a 1-mg/cm^2 target onto which a 15-mg/cm^2 Au or Pb layer was evaporated. All data sets were taken with the Argonne-Notre Dame γ-ray facility and contain in excess of 10^8 events from which high multiplicity γ-ray cascades in the nuclei of interest can be extracted through suitable total multiplicity and sum-energy gating.

The experimental investigation of the level structures of all three nuclei is now complete. In ^{188}Hg, two distinct types of rotational structures emerge. One type is based on the ground state and corresponds to the rotation of an oblate, collective nucleus ($\beta_2 \sim 0.15$, $\gamma = -60°$, in the Lund convention). A total of 7 band structures are 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 ($\beta_2 \sim 0.2$, $\gamma = 0°$) which is known for some time to coexist with the oblate structures at low and moderate spin. In ^{189}Hg and ^{190}Hg several band structures were observed as well. In these cases it appears that the rotational structures are all associated with oblate collective rotation. However, in each nucleus other level sequences which display a more irregular pattern were also seen. It is thought that these sequences may correspond to a departure from axial symmetry. The situation appears to have some similarities with that observed in previous studies of ^{191,192}Hg which were described in earlier reports.

Total Routhian surface calculations were performed for all three nuclei in order to investigate the available deformation space and determine the deformation parameters for which pronounced minima in the total energy occur. These calculations then become the starting point for detailed cranked shell-model calculations in which one tries to understand the various band crossings seen in the data. These calculations are still in progress. We expect to complete this work in the spring of 1993. At this point the results for all three nuclei will be written up both as publications and as a thesis report. This work is part of the thesis project of I. G. Bearden.[1]

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*Resident Graduate Student from Purdue University, †Purdue University, ‡University of Notre Dame, §Idaho National Engineering Laboratory

[1] D. Ye et al., Nucl. Phys. A537, 207 (1992).

b.2. M1 Bands and Oblate Collectivity in ^{195,196}Pb (Y. Liang, R. V. F. Janssens, M. P. Carpenter, I. Ahmad, R. G. Henry, T. L. Khoo, T. Lauritsen, W. Reviol,* U. Garg,* I. G. Bearden,† P. J. Daly,* B. Fornal,‡ R. Mayer,‡ M. W. Drigert,§ and F. Soramel¶)

The study of superdeformation (SD) in the ^{195,196}Pb isotopes described in section B.a.3. above provided a data set of such quality that it allowed us to perform a v. ry detailed study of the yrast and near-yrast level structure of these nuclei. Of particular ir terest here is the investigation of rotational sequences of M1 transitions which were obsen ed very recently in several Pb isotopes at moderate spin and excitation energy.[1] These ΔI= 1 bands are generally characterized by large B(M1)/B(E2) ratios, which are characteristic of high-K

*University of Notre Dame, †Resident Graduate Student from Purdue University, ‡Purdue University, §Idaho National Engineering Laboratory, ¶University of Padova, Italy, [1]See for example, A Kuhnert et al., Phys. Rev. C 46, 133 (1992).

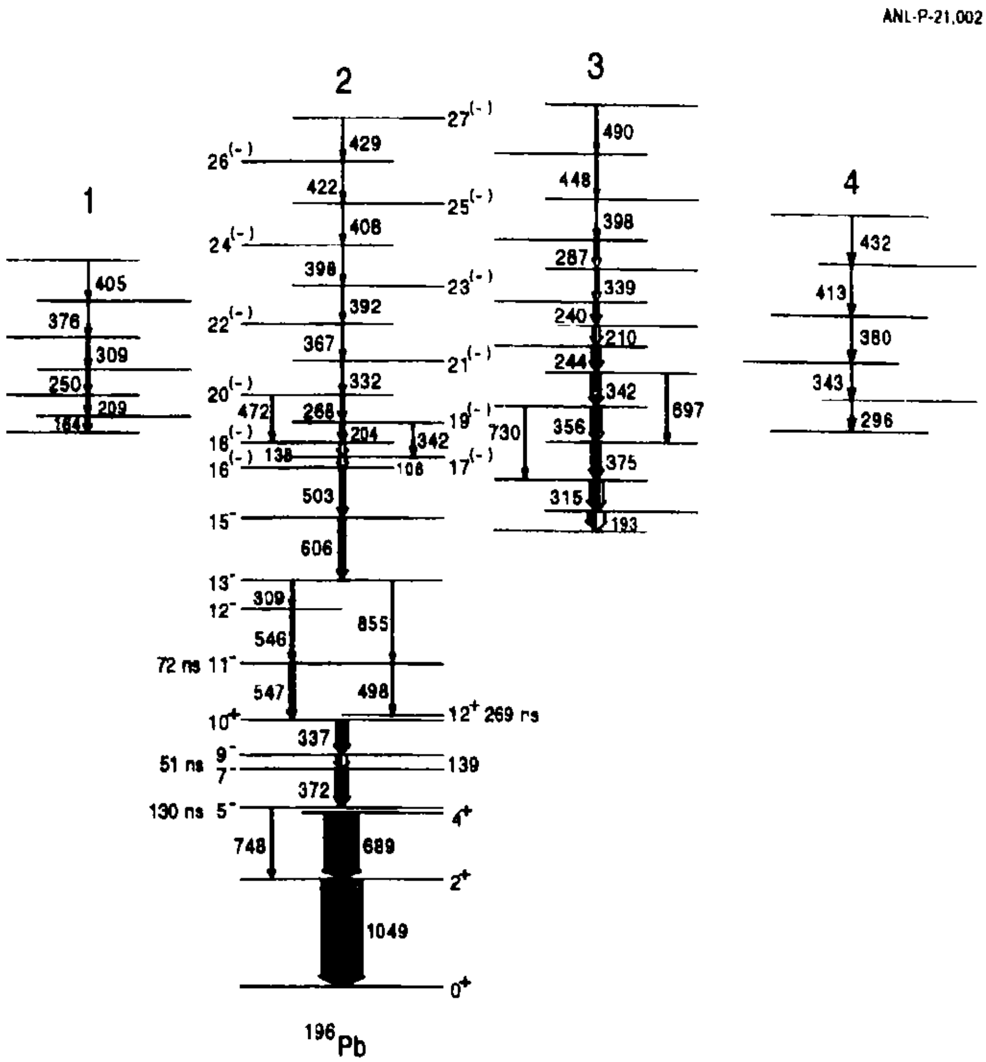

Fig. I-11. Partial level scheme for ^{196}Pb showing the four M1 bands identified in this nucleus with the ^{170}Er(^{30}Si,4n) reaction.

proton configurations. There is also evidence that these bands are characterized by large amounts of aligned angular momentum. In most cases known thus far it has not been possible to observe the transitions linking the M1 bands with the known yrast states and, as a result, the configurations associated with this new type of collectivity have generally not been firmly established. From the data obtained with the $^{170}Er(^{30}Si$, 4n and 5n)$^{196,195}Pb$ reactions we were able to observe numerous dipole bands of the type described above. More precisely, four M1 bands were observed in ^{196}Pb (see Fig. I-11). Three of these bands are "regular", i.e. the transition energies increase smoothly with spin, suggesting a rotational behavior. The other band is "irregular", i.e. it does not display this behavior. For the strongest of the regular bands, excitation energies, spins and probable parities were established from the observation of linking transitions to the yrast states. Four M1 bands were also established in ^{195}Pb, two of which are regular. In this case linking transitions were observed for the two irregular bands (see Fig. I-12).

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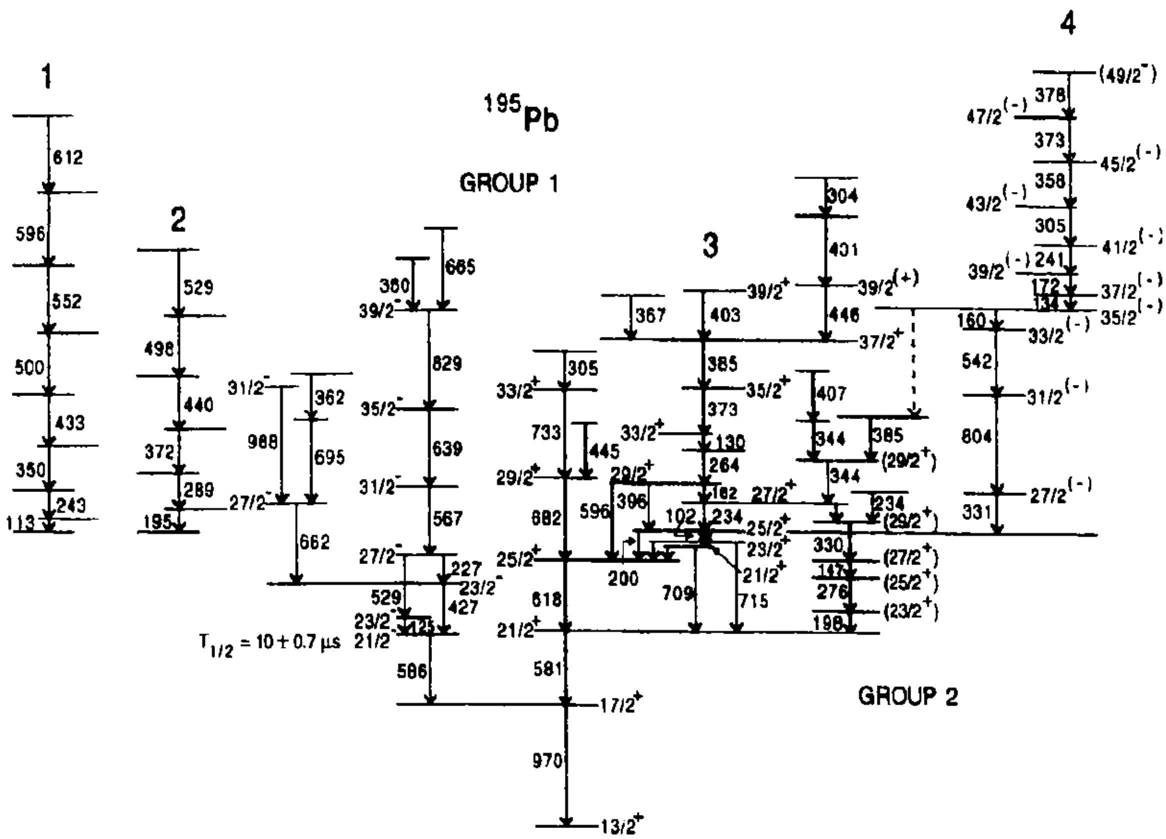

Fig. I-12. Level scheme for ^{197}Pb. The M1 bands are marked 1-4.

Detailed Total-Routhian-Surface calculations (TRS) and Cranked Shell-Model calculations (CSM) were performed for ^{196}Pb in order to understand the data. The regular band for which the decay into the yrast states was delineated is proposed to be built on deformation aligned high-j, shape-driving quasiproton excitations across the Z = 82 shell gap ($h_{9/2} \otimes i_{13/2}$) coupled to rotation- aligned $i_{13/2}$ quasineutron excitations. The other regular bands are presumably of the same character and the calculations indicate that other quasiparticle configurations involving high-j orbitals are available near the Fermi surface. The interpretation of the irregular band is more of a challenge. It is possible that this band is associated with configurations either departing from axial symmetry or for which the potential energy surface is at least soft in the γ degree of freedom. TRS calculations indicate that configurations where $s_{1/2}$ or $d_{3/2}$ proton orbitals replace one of the high-j orbitals might be involved. Presently, TRS and CSM calculations continue in order to understand the M1 bands of ^{195}Pb.

Three of the M1 bands in ^{196}Pb were also observed in a separate experiment performed at Berkeley and a joint paper reporting the results of the two measurements was submitted recently for publication.[2] We are preparing a separate full account of our results on both nuclei for publication. We hope to be able to measure the lifetimes of some of the states in these dipole bands in a forthcoming experiment.

[2] J. R. Hughes, Y. Liang et al., Phys. Rev. C 47, R1337 (1993).

b.3. Collective and Quasiparticle Structures in ^{192}Pb (M. P. Carpenter, R. V. F. Janssens, I. Ahmad, T. L. Khoo, T. Lauritsen, Y. Liang, A. J. M. Plompen,* M. N. Harakeh,* W. H. A. Hesseling,* G. Van't Hof,* N. Kalentar-Nayestanaki,* J. P. S. van Schagen,* U. Garg,† W. Reviol,† D. Ye,† and I. G. Bearden‡)

As indicated in section B.a.4., an experiment was performed with the aim of measuring lifetimes in the superdeformed band of ^{192}Pb. While the superdeformed band could not be found, it has been possible to perform detailed studies of the yrast and near- yrast states in this nucleus from the data collected in this experiment. The structure of ^{192}Pb was investigated at ATLAS with the ^{173}Yb(^{24}Mg,5n) reaction at a beam energy of 132 MeV. The 0.9-mg/cm^{2}- thick ^{192}Pb target was evaporated on a 15-mg/cm^{2}- thick ^{nat}Pb backing in which the recoils were stopped. The measurement was performed with the Argonne Notre Dame BGO γ-ray facility. The level scheme was extended up to an excitation energy of 7 MeV and a spin of 23 $\hbar$ (see Fig. I-13).

Two collective bands of levels linked by M1 transitions and four groups of states of non-collective character were observed. M1 bands of this type were observed in several Pb isotopes (see preceding contribution) and the present case is one of the few where the excitation energy of these "oblate collective" structures could be determined. Based on comparisons with experimental data on odd-A Tl isotopes and with cranked shell-model calculations assuming an oblate shape, the collective M1 bands are interpreted as having an

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underlying deformation- aligned two quasiproton configuration coupled to a pair rotation-aligned $i_{13/2}$ quasineutrons. The four groups of non-collective level sequences are all based on isomeric states which can be understood as quasiparticle excitations within the spherical shell model. Two of these sequences are interpreted as resulting from the coupling of the 2^+, 4^+, 6^+ and 8^+ quasiparticle excitations coupled to maximally aligned two quasineutron excitations. The two other excitations are most likely of the same character, but precise configurations are not being proposed because the available experimental information is more limited and does not allow for unambiguous interpretation. The level scheme of ^{192}Pb can be regarded as a good example of the intriguing and complex interplay between collective and single- particle degrees of freedom which occurs at moderate and high spins in nuclei near the doubly-magic ^{208}Pb nucleus.

The single-particle sequences reported here are currently the subject of more detailed theoretical calculations by J. Blomqvist and collaborators in Stockholm. This work is part of the thesis of A. J. M. Plompen. A paper describing these results was submitted recently for publication.

b.4. <u>**Detailed Spectroscopy of High-Spin States in ^{193}Tl**</u> (M. P. Carpenter, R. V. F. Janssens, I. Ahmad, P. B. Fernandez, T. L. Khoo, E. F. Moore,* W. Reviol,† U. Garg,† D. Ye,† I. G. Bearden,‡ Ph. Benet,§ P. J. Daly,§ M. W. Drigert,¶ and S. Pilotte||)

A recent spectroscopic study on ^{193}Tl carried out at ATLAS 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}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}Gd(^{37}Cl,4n) reaction at 168 MeV. The larger data set (200×10^6 events) was taken using a thin target, and the smaller data set (10×10^6 events) was taken with a thick target where all recoiling evaporation residues were stopped at the target position. The γ decay of ^{193}Tl was measured using the Argonne-Notre Dame BGO γ-ray facility and the 168-MeV ^{37}Cl beam was supplied by ATLAS. In the off-line analysis, the relative yield of high-spin states in ^{193}Tl was enhanced by gating on higher BGO multiplicity (≥12). With this constraint, the 4n reaction channel was enhanced and represented approximately 80% of the 50×10^6 events incremented in a γ-γ coincidence matrix using the thin target data. Two major γ sequences of opposite parity were established from the data. The negative-parity sequence was observed up to a spin of $41/2\ \hbar$ and an excitation energy of 6.1 MeV while the positive-parity sequence was extended to $I = 41/2^{(+)}\ \hbar$ 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 $I \sim 29/2\ \hbar$.

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*University of Rochester, †University of Notre Dame, ‡Resident Graduate Student from Purdue University, §Purdue University, ¶Idaho National Engineering Laboratory, ||University of Tennessee, [1]D. Ye et al., Nucl. Phys. A537, 207 (1992), [2]W. Reviol et al., Nucl. Phys. <u>A548</u>, 331 (1992).

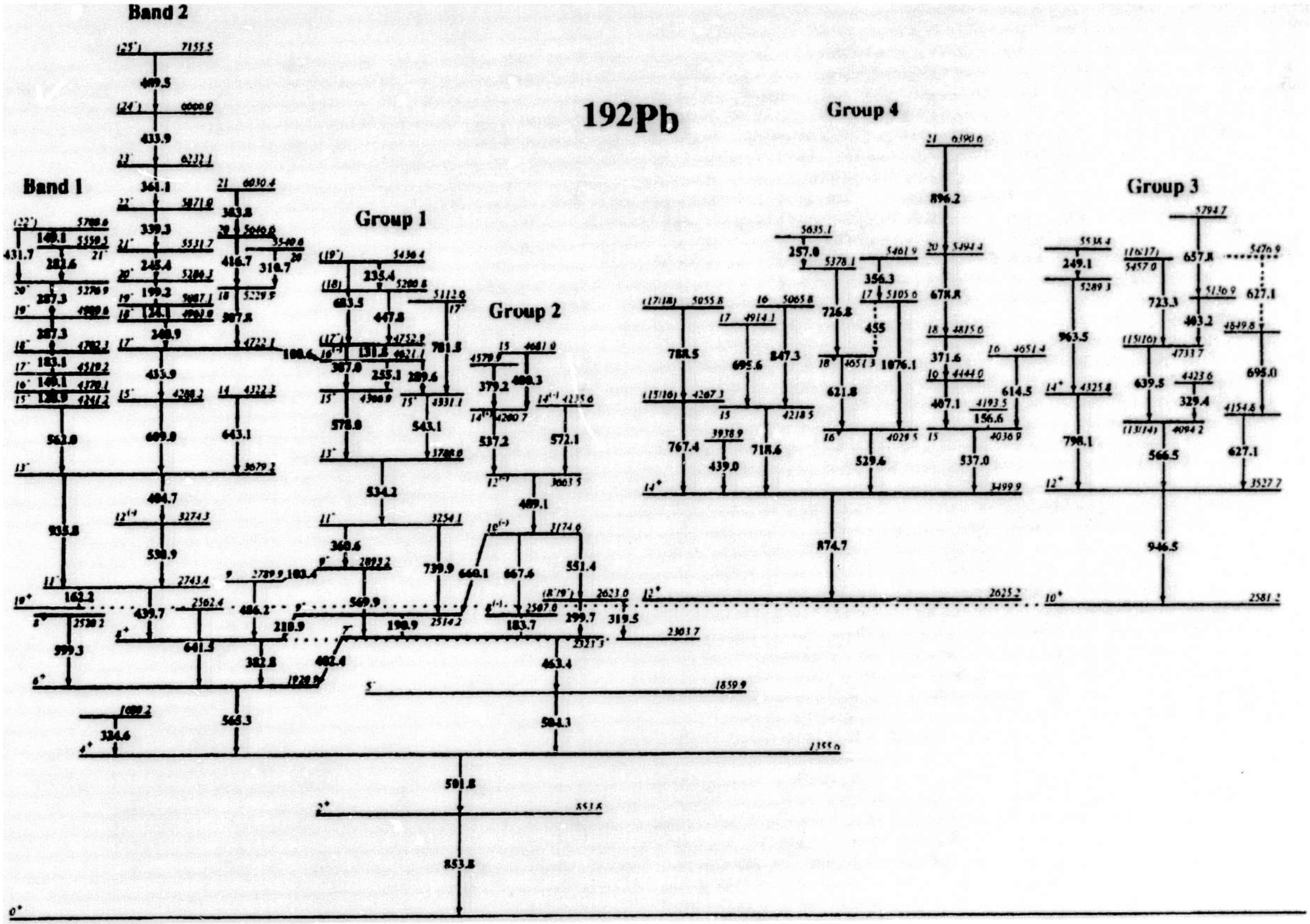

Fig. I-13. Level scheme proposed for the ^{192}Pb nucleus. Bands 1 and 2 are the two M1 collective structures. The non-collective structures are given by groups 1-4.

These two band sequences were interpreted in the context of mean- field calculations. In the theoretical analysis, we used available Total Routhian surfaces (TRS) calculations which were 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}Tl, the negative-parity sequence is identified as a rotational band built upon a high-Ω $h_{9/2}$ 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}Hg which was also studied in great detail by our group.[1] A paper discussing this work was published recently.[2]

b.5. **<u>Structure Studies in the Light Hg Isotopes from Gamma-FMA Coincidence Measurements</u>** (R. G. Henry, R. V. F. Janssens, M. P. Carpenter, C. Davids, T. L. Khoo, T. Lauritsen, Y. Liang, I. G. Bearden,* B. Fornal,† R. M. Mayer,† D. Nissius,† M. W. Drigert,‡ W. Reviol,§ W. Chung,§ and K. Bindra¶, F. Soramel‖)

We have recently completed the first experiment at the FMA where the device was used in conjunction with 10 Compton-Suppressed Ge detectors located at the target position. The main purpose of the experiment was to evaluate the capabilities of the setup in a case where (1) several reaction channels of widely different relative yields are present, (2) where weak gamma-ray branches are present (to study the limits of detection sensitivity), (3) where isomers occur (which affect the FMA transmission and allow the investigation of the use of thin C foils to reset the charge-state distribution of the recoils), and (4) where some new interesting physics questions may be addressed.

We investigated the ^{160}Gd(^{36}S,xn) reactions leading to Hg nuclei at beam energies of 159, 164 and 167 MeV. Three types of events were written to magnetic tape: γ-γ coincidence events, γ-FMA coincidences (i.e. events where a signal is present in the focal plane PPAC detector of the FMA) and γ-γ-FMA triple coincidence events. The analysis is still under way. In a first step our efforts have concentrated on the understanding of the transmission through the FMA. Long-lived isomeric states ($\tau \geq 10$ ns) are present in ^{190}Hg and ^{192}Hg. Internal conversion will alter the charge-state distributions during the flight of the recoiling nuclei. Mass yields were extracted with and without a thin "reset" carbon foil located at 30-cm (167 and 164 MeV data) or at 3-cm (159-MeV data) downstream of the target. The mass resolution with and without the reset foils has was determined. A careful study was performed of the suitability of the various measured parameters (energy loss in PPAC, time and position information etc.) for optimal gating of the mass spectra in subsequent sortings of the γ-ray spectra. In a second phase, we are now concentrating our efforts on the analysis of the γ-FMA and γ-γ-FMA events. This phase is still in progress. The sensitivity of the detection system is such that we were able to obtain the mass spectrum in coincidence with the superdeformed band of ^{192}Hg. This is illustrated in Fig. I-14. The analysis will be completed soon. The results will be summarized in a technical publication.

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*Resident Graduate Student from Purdue University, †Purdue University, ‡Idaho National Engineering Laboratory, §University of Notre Dame, ¶Vanderbilt University, ‖University of Padova, Italy

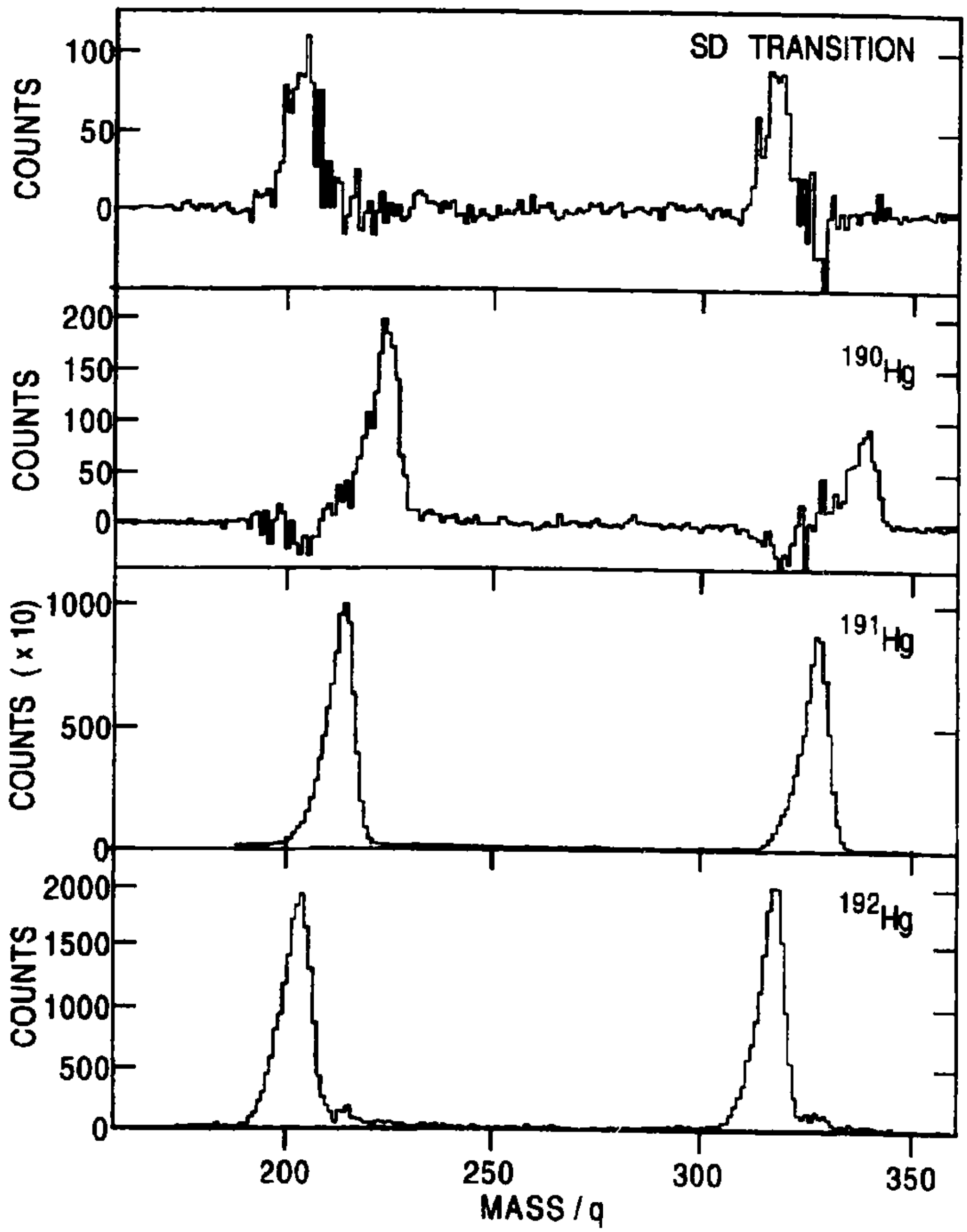

Fig. I-14. Mass spectra in coincidence with yrast γ-ray transitions in $^{190,191,192}Hg$ as well as with the 342-keV transition in the superdeformed band of ^{192}Hg. The two peaks in each panel of the figure correspond to different charge states.

b.6. Structures and Shapes of Neutron-Rich Fission Fragments (I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, L. R. Morss,* K. L. Nash,* C. W. Williams,* W. R. Phillips,† J. L. Durell,† F. Liden,† C. J. Pearson,† J. A. Shannon,† B. J. Varley,† N. Schulz,‡ M. Bentaleb,‡ E. Lubkiewicz,‡ and C. J. Lister§)

In the past we utilized the high sensitivity of the Argonne-Notre Dame BGO gamma-ray array to investigate the structures of nascent fission fragments.[1] Using a ^{248}Cm spontaneous fission source, we were able to determine level schemes of many neutron-rich nuclei in the mass-100 and mass-146 regions. The high-quality data from the last experiment allowed us to develop a new technique to identify transitions in nuclei previously unknown. In the mass- 146 region, our data showed that ^{146}Ba and ^{146}Ce develop octupole deformation at spin >7 $\hbar$ and a very large quadrupole deformation ($\beta_2 = 0.4$) was deduced for ^{102}Zr and ^{104}Zr. We performed a similar experiment with the EUROGAM facility at Daresbury, which is currently the world's most powerful gamma-ray array. Five low- energy-photon spectrometers from Yale were added to the setup so that fragment K X rays and low-energy gamma rays could also be measured. The ^{248}Cm source was prepared in the Argonne Chemistry Division by mixing 5-mg curium oxide with 65-mg KCl and pressing it under high pressure. The 7-mm diameter Cm pellet was shipped to Daresbury for the experiment. We collected data for 5 days and accumulated 18 exabyte tapes of data. This large amount of data will enable us to use triple- and higher-fold coincidences to generate gamma-ray spectra with very low background. We hope to detect transitions with intensities one tenth the detection limit in our last experiment. This sensitivity will enable us to identify several new neutron-rich nuclides. The data are currently being analyzed.

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*Chemistry Division, ANL, †University of Manchester, England, ‡CRN, Strasbourg, France, §Yale University, [1]See for example M.A.C. Hotchis et al., Nucl. Phys. A530, 111 (1991).

b.7. Spectroscopy of Neutron-Rich Products of Heavy-Ion Collisions (M. P. Carpenter, R. G. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, I. G. Bearden,* B. Fornal,† R. H. Mayer,† D. Nisius,† M. Sferrezza,† P. J. Daly,† Z. W. Grabowski,† and F. Soramel‡)

Experiments proposed for the new large γ-ray detector arrays mostly emphasize the improved prospects for studying nuclei produced in compound nuclear reactions. Studies of nuclei produced in non-fusion channels are comparatively neglected. In particular, the undeveloped field of spectroscopy of neutron-rich nuclei, which are major products of deep-inelastic heavy-ion reactions, remains open for exploration. We have made a start by examining γ-γ coincidence data - including non-fusion events - from several recent thick-target ATLAS experiments.

The most complete data analyses were performed for the systems $^{122,124}Sn$ + 325 MeV ^{76}Ge and $^{122,124}Sn$ + 344 MeV ^{80}Se. These particular studies were undertaken to explore the yrast spectroscopy of heavy tin nuclei which are not accessible by fusion-evaporation. The in-beam and off-beam γ-ray data obtained were found to include

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*Resident Graduate Student from Purdue University, †Purdue University, ‡University of Padova, [1]R. Broda et al., Phys. Rev. Lett. 68, 1671 (1992), [2]R. H. Mayer et al., Z. Phys. A342, 247 (1992).

new information about more than 40 nuclei around A = 124 and A = 80. These are products of deep-inelastic reactions involving transfer of many nucleons between target and projectile. Population of excited states with moderately high spins is observed. The data analysis yielded many interesting features including: (a) long-lived $(\nu h_{11/2})^n$ seniority, $v = 2, 10^+$ isomers in ^{122}Sn and ^{124}Sn. The data on the B(E2) values allowed us to establish the half-filling of the $\nu h_{11/2}$ subshell close to N = 73 and provided a revealing comparison with less complete results for N = 83 isotones and Z = 82 isotopes; (b) microsecond M2 isomers in ^{119}Sn, ^{121}Sn and ^{123}Sn have been characterized and interpreted. In ^{119}Sn and ^{121}Sn, higher-lying nanosecond E2 isomers of $(\nu h_{11/2})^n$ $v = 3$ character have also been identified; (c) Yrast cascades have been identified for the first time in the odd nuclei $^{121-125}$Sb and $^{115-119}$In; and (d) new spectroscopic information has also been derived for the neutron-rich products around A = 80, including $^{72-74}$Zn, $^{76-78}$Ge and $^{80-84}$Se.

We were also able to examine thick target γ-γ data for the system ^{130}Te + 262 MeV ^{60}Ni which were originally taken as part of a superdeformation study in the Hg isotopes. We identified yrast cascades in ^{126,128,130}Te and in the semi-magic nuclei ^{64,66}Ni. Partial results on points (a) and (b) above have been published.[1,2] Further experiments are planned. One of the major aims is to provide further evidence for isotopic assignments to some of the nuclei observed in our studies.

b.8. Studies of Yrast Isomers in the Exotic N = 81 Nucleus ^{151}Yb Using the Fragment Mass Analyzer (C. N. Davids, I. Ahmad, B. B. Back, M. P. Carpenter, D. Henderson, R. G. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, I. G. Bearden,* D. Nissius,† B. Fornal,† R. Broda,† R. M. Mayer,†P. J. Daly,† Z. W. Grabowski,† W. Chung,‡ K. Bindra,§ A. V. Ramayya,¶ and F. Soramel||)

Recoil products from the reaction ^{96}Ru + 255 MeV ^{58}Ni were analyzed using the Argonne Fragment Mass Analyzer (FMA), and transported to a collector foil behind the focal plane, where decays of μs isomers could be studied under low background conditions. The recoils were dispersed in A/q as they traversed the position-sensitive focal detector, and recoil γ-ray coincidences could thus be used to assign masses for specific γ-ray cascades. By use of these methods, yrast isomers with half-lives of 2.6(1) μs and 20(1) μs were firmly assigned to the neutron-deficient N = 81 nucleus ^{151}Yb, and the main features of the isomeric decays were established (see Fig. I-15). A paper describing this work will appear in the Physical Review.[1]

These results came from the first test experiment of this kind with the Argonne FMA, and much higher detector sensitivity should be achievable in future experiments. A particularly important improvement will be the installation of Si detectors around the catcher foil for measuring conversion electrons from stopped product nuclei.

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*Resident Graduate Student from Purdue University, †Purdue University, ‡University of Notre Dame, §Resident Graduate Student from Vanderbilt University, ¶Vanderbilt University, ||University of Padova, Italy, [1]D. Nissius et al., Phys. Rev. C, in press.

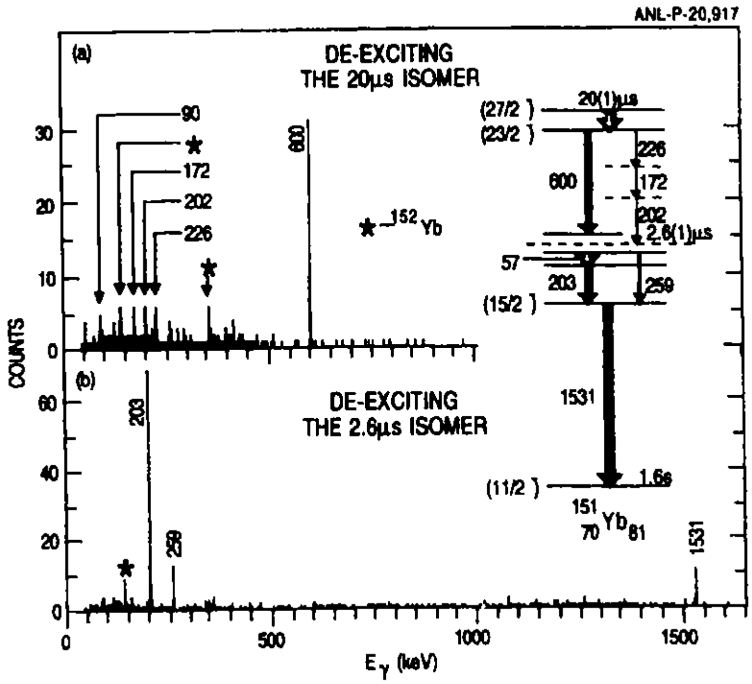

Fig. I-15. Gamma rays observed at the FMA focal plane from the decay of high-spin isomers in ^{151}Yb.

b.9. High-Spin Gamma-Ray Spectroscopy of $^{96-98}$Ru (M. P. Carpenter, I. Ahmad, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, W. Reviol,* U. Garg,* A. Aprahamian,* B. Davis,* S. Naguleswaran,* J. C. Walpe,* D. Ye,* and I. G. Bearden†)

It has been predicted by Aberg that nuclei with mass 90-100 (e.g. ^{96}Ru) exhibit collective rotation associated with a "dumb-bell" 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 γ decay of these nuclei was measured with the Argonne-Notre Dame BGO 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 dumb-bell shape was found. The expected signature of this band would be similar to that for a superdeformed band, i.e. a dynamic moment of inertia which is large and nearly constant. However, we established from the coincidence data gated on BGO multiplicities $K \geq 8$ and $K \geq 15$ two main band structures in ^{96,97,98}Ru, and thus extended significantly the previously-known high-spin level structure of all three nuclei. The proposed level scheme for ^{96}Ru is given in Fig. I-16. The γ transitions observed in one of these two structures suggest that this sequence is rotational in character and co-exists with the near-spherical ground state, i.e. the transitions connecting levels in these sequences are stretched quadrupoles and show a smooth increase in energy with increasing spin.

*University of Notre Dame, †Resident Graduate Student from Purdue University

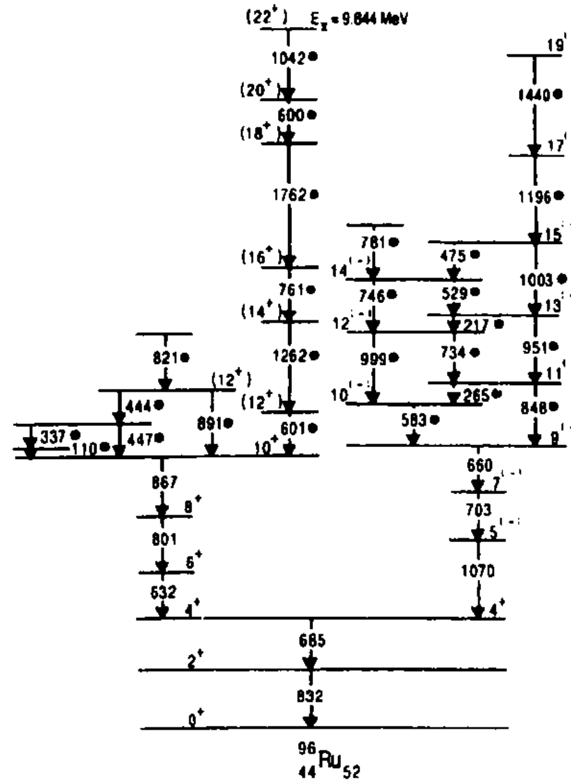

Fig. I-16. Partial level scheme of ^{96}Ru involving the strongest γ transitions for K ≥ 8. Newly-observed tgransitions are marked with a dot. The spin - and parity assignments, given in parentheses, are preliminary.

Recent Total Routhians Surface (TRS) calculations predict the existence of deformed prolate neutron configurations with negative parity in all three Ru nuclei at near yrast energies. The configurations associated with these minima involve the $\nu h_{11/2}$ orbital and the deformations are quite small ($\beta_2 < 0.13$). According to these calculations, an addition of a pair of aligned $g_{9/2}$ protons is important in stabilizing these minima. For ^{97}Ru, the favored configuration for the collective band is $|\nu h_{11/2} \otimes (\pi g_{9/2})^2|$. For the even-A nuclei, the neutron configuration associated with these minima is $|\nu h_{11/2} \otimes \nu g_{7/2}|$. Calculations are continuing.

b.10. <u>Yrast Decays in ^{43}K</u> (R. V. F. Janssens, R. Holzmann,* T. L. Khoo, W. C. Ma,† R. L. Kozub,‡ C. R. Bybee,‡ M. M. Hindi,‡ J. F. Shriner, Jr.,‡ M. W. Drigert,§ U. Garg,¶ and J. J. Kolata¶)

The present work, which is the first heavy-ion induced in-beam γ-ray study of ^{43}K, was undertaken to obtain a better picture of the high-spin structure of this nucleus. The Argonne Notre Dame BGO γ-ray facility was used to observe coincident events between charged particles and γ rays emitted from fusion-evaporation reactions of 100-MeV ^{36}S ions with ^{9}Be target nuclei. Threefold ($p\gamma_1\gamma_2$) coincidence data and γ-ray intensity ratios were used to establish a decay scheme and identify negative- and positive-parity yrast decay

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*Present address: GSI, Darmstadt, Germany, †Present address: Vanderbilt University, ‡Tennessee Technical University, §Idaho National Engineering Laboratory, ¶University of Notre Dame, [1]R. L. Kozub et al., Phys. Rev. C 46, 1671 (1992).

chains. Two stretched-E2 yrast decay chains of opposite parity were observed, both with a highest spin state of $15/2\hbar$. Energies of the positive-parity levels predicted in the shell-model calculations of Johnstone are in good agreement with the experiment. The model space includes the $(f_{7/2})^4(d_{3/2}s_{1/2})^{-1}$ and the $(f_{7/2})^3(p_{3/2}d_{3/2})^{-1}$ configurations and the parameters of the neutron and the particle-hole interaction were determined by fits to the energy levels of Ca and K isotopes. No theoretical calculations for the negative parity states in ^{43}K have been published to our knowledge. A paper reporting these results was published recently.[1]

b.11. **Statistical Spectrum and Level Densities in ^{174}Hf** (T. L. Khoo, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, E. F. Moore, L. P. Farris,* M. J. Brinkman,* J. A. Cizewski,*R. G. Henry,* C. S. Lee,* J. J. Kolata,† K. Beard,† U. Garg,† D. Ye,† C. Kaplan,† D. Winchell,† and J. Saladin‡)

We measured the γ spectra from ^{174}Hf produced with the (α,2n) reaction using beams from the Notre Dame FN tandem accelerator. The γ rays were detected in an array consisting of 6 Compton- suppressed Ge detectors and 14 BGO hexagons from the University of Pittsburgh. One aim of this experiment was to extract information on the γ strength function and on the level densities from the shape of the continuous statistical spectrum of ^{174}Hf. For this purpose it is preferable to measure the spectral shape of the

statistical component using the (α,2n) reaction instead of (HI,xn) reactions since the input angular momentum is smaller ($\ell < 14\hbar$) with α-induced reactions. Thus, the E2 bump from continuum transitions preceding the discrete line decay (normally a dominant feature in reactions with large ℓ) is quite small. After subtraction of the discrete lines we obtained the statistical spectrum.

The data analysis is essentially complete and L. Farris is writing up his Ph.D. dissertation on this work. Calculations were also 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. At energies below 0.5 MeV, the measured quasicontinuum yield is larger than the calculated one. The excess transitions probably arise from transitions in the vicinity of the yrast line and may contain significant M1 contributions from high-K bands, which were not included in the calculations. Additional work will be undertaken to explore the sensitivity to variations in the level density and, in particular, to search for any evidence for quenching of pairing with thermal excitation.

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b.12. Yrast Structure of the N = 84 Nucleus ^{136}Te (I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, L. R. Morss,* J. A. Cizewski,† Ph. Benet,‡ D. Ye,§ M. A. C. Hotchkis,¶ J. L. Durell,¶ J. Copnell,¶ A. S. Mowbray,¶ J. Fitzgerald,¶ and W. R. Phillips¶)

The Yrast structure of the N = 84 nucleus ^{136}Te was determined for the first time. These levels were deduced from the gamma- gamma coincidence measurements on the nascent fragments produced in the spontaneous fission of ^{252}Cf and ^{248}Cm. The experiments were performed with the Argonne-Notre Dame BGO gamma-ray facility. The transitions in ^{136}Te were observed in spectra gated by gamma rays in ^{108,109,110}Ru. The gamma rays were assigned to ^{136}Te on the basis of gamma-ray yields in the complimentary Ru fragments. These assignments were confirmed by showing that these gamma rays are also in coincidence with transitions in Pd isotopes produced in the decay of ^{252}Cf. Yrast states up to spin-parity 10^+ were identified in ^{136}Te (see Fig. I-17). The data show that the low-lying states in ^{136}Te are predominantly two-neutron $2f_{7/2}$ and two-proton $1g_{7/2}$ in character. A paper summarizing these results has been submitted for publication.[1]

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*Chemistry Division, ANL, †Rutgers University, ‡Purdue University, §University of Notre Dame, ¶University of Manchester, England, [1]J. A. Cizewski et al., Phys. Rev. C 47, 1234 (1993).

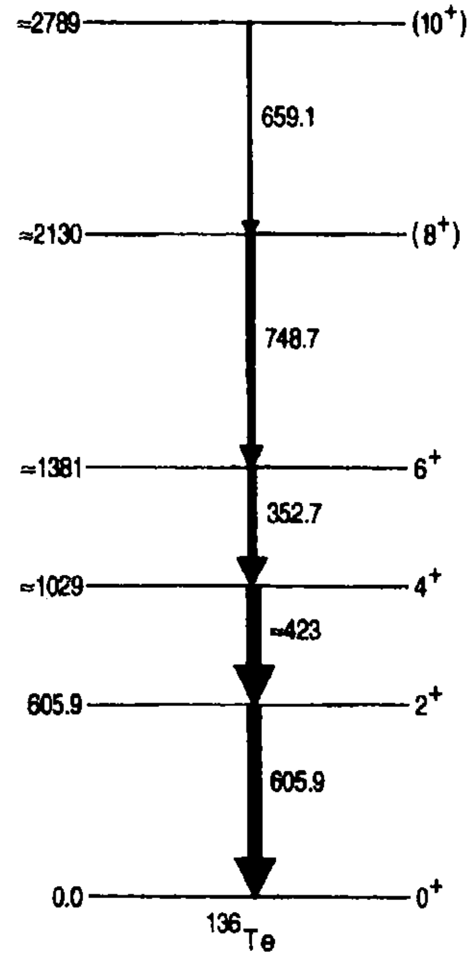

Fig. I-17. Proposed level spectrum of ^{136}Te. Spin-parity assignments are based on expected systematical behavior.

b.13. Yrast Spectroscopy of ^{196}Po (M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, L. A. Bernstein,* J. A. Cizewski,* H. Q. Jin,* R. G. Henry,*† L. P. Farris,* and I. G. Bearden‡)

Recently, much work was done on the level structure of nuclei centered around N = 112 and Z = 80. From these studies, it has become clear that nuclei in this region exhibit a rich variety of shapes. For example, excited γ-ray sequences were found in Pb nuclei of this region which are rotational in character while the yrast structure is clearly single-particle in nature. This is in contrast to the Hg isotopes whose near-yrast structure is dominated by rotational bands at low and medium spins, but which co-exist with non-collective excitations around $I = 20\,\hbar$. The polonium isotopes with two valence protons outside a Pb core should also provide us with information concerning the transition between single-particle and collective behavior in the nuclear system. For example, Po nuclei with N ~ 126 have structure characteristics of shell-model behavior, but as the number of neutrons is decreased, the large number of valence particles makes a shell-model description of the low-lying structure difficult and the onset of collective structure is expected.

In order to study the level structure of ^{196}Po, the ^{172}Yb(^{28}Si,4n) reaction at beam energies of 141 and 145 MeV was utilized. Approximately 35×10^6 Ge - γ-γ events were recorded with the Argonne-Notre Dame BGO γ-ray facility with the requirement that the array multiplicity (K) was ≥ 3. Fission and multi- particle transfer channels were suppressed in the Ge data by requiring that K ≥ 5 in the off-line analysis. This analysis has extended the level structure of ^{196}Po to a spin of 13 $\hbar$ and an excitation energy of 3.6 MeV. The proposed level scheme is given in Fig. I-18.

One of the more simple analyses to perform in order to ascertain whether an yrast sequence exhibits either single-particle or collective behavior is to take ratios of various yrast transition energies. By plotting the $8^+/6^+$ ratio of level energies (R(8/6)) against the $6^+/4^+$ ratio (R(6/4)) for even-even Po isotopes ranging from N = 126 to N = 112 (^{210}Po to ^{196}Po), one discovers that only ^{196}Po enters the collective regime of the plot (R(8/6) ≥ 1.33). The ratios for the other Po isotopes clearly lie in the single-particle regime. This is in contrast to Te, which has two-valence protons outside the Z = 50 shell, where similar ratios show a smooth tracking from the single-particle to collective regime as the number of valence neutrons increases. Additional support that the low-lying structure of ^{196}Po is vibrational comes from relative B(E2) ratios of non-yrast transitions which are consistent with the vibrational model. It is proposed that the mechanism which drives ^{196}Po to the collective regime is a larger overlap between the occupied $\nu i_{13/2}$ intruder orbital and the valence proton orbital when compared to the heavier Po isotopes. This larger overlap corresponds to a larger p-n residual interaction, which in turn drives the collective motion.

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*Rutgers University, †Present Address: Argonne National Laboratory, ‡Resident Graduate Student from Purdue University

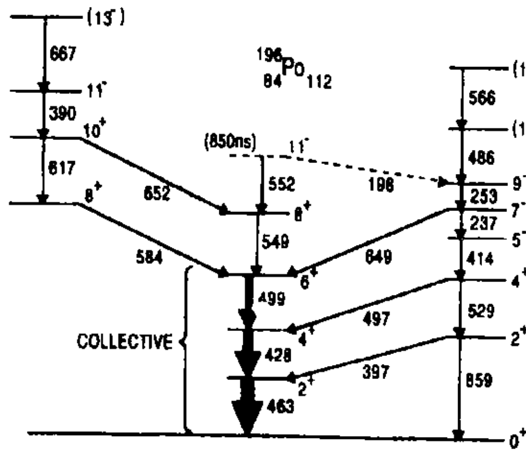

Fig. I-18 Level scheme of ^{196}Po obtained with the ^{172}Yb(^{28}Si,4n) reaction.

b.14. High-Spin Isomers and Highly K-Violating Decays in ^{176}W
(I. G. Bearden,* M. P. Carpenter, R. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, B. Crowell,† P. Chowdhury,† S. J. Freeman,† C. J. Lister,† and F. Soramel‡)

The nucleus ^{176}W was studied using the Argonne-Notre Dame BGO array and the ^{150}Nd(^{30}Si,4n) reaction. Several new high-spin isomers were observed, including one, with $J^{\pi} = 14^{+}$ and $t_{1/2}$ = 70 ns, which exhibits extremely unusual modes of decay. High-spin isomeric states such as these were observed before in ellipsoidally deformed nuclei in the A ~ 180 region, and interpreted as states whose (non-collective) rotation is about the symmetry axis of the nucleus.

The gamma-decay of such non-collective high-spin states is strongly influenced by approximate conservation of the K quantum number, defined as the projection of the total angular momentum along the axis of symmetry. The isomeric states are interpreted as having K = J, in contrast to the most-bound states of a given spin, which typically (although not always) have K = 0. The pattern of decay almost universally observed until now is one of minimizing the change in K incurred by each transition. The decay of the K = 14 state in ^{176}W is highly anomalous, in that the majority of the decay branches leap directly to K = 0, and no transitions were observed to the available states with intermediate K-values. A large amount of complementary spectroscopic data was obtained in this experiment on states in ^{176}W with intermediate K-values.

The oldest accepted model of K-violating decays involves K-mixing due to Coriolis coupling, which may be visualized as a wobbling motion. The observation of very unusual patterns of decay for this isomer led to extensive theoretical calculations as part of the present work to understand the decay in terms of coupling to fluctuations in the shape degrees of freedom of the nucleus, rather than wobbling with a fixed shape. Early results of the calculations are promising.

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*Resident Graduate Student from Purdue University, †Yale University, ‡University of Padova, Italy

b.15. First Identification of In-Beam γ Rays in $^{181,183}Hg$ (K. S. Bindra,* W. C Ma,† B. R. S. Babu,† A. V. Ramayya,† J. H. Hamilton,† L. Chaturvedi,† J. Kormicki,† C. N. Davids, I. Ahmad, I. G. Bearden,‡ M. P. Carpenter, W. Chung,§ D. J. Henderson, R. G. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, H. Penttilä,¶ and F. Soramel||)

Neutron-deficient Hg isotopes were produced by the $^{155}Gd(^{32}S,xn)$ reaction at 160 and 190 MeV. Ten detectors of the Argonne-Notre Dame Compton-Suppressed Germanium array were placed around the FMA target chamber and used to measure prompt gamma-rays. Reaction recoils entered the FMA and were identified by their mass at the focal-plane. The insertion of a charge-state resetting foil directly behind the target increased the focal plane yield of Au ions of the same mass. This is due to the presence of several transitions proceeding by internal conversion in the Au isotope. Coincidence data including FMA-γ, γ-γ, and FMA-γ-γ were taken. A number of transitions were identified in ^{181}Hg and ^{183}Hg. Further analysis of the data is under way.

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*Resident Graduate Student from Vanderbilt University, †Vanderbilt University, ‡Resident Graduate Student from Purdue University, §University of Notre Dame, ¶Joint appointment, University of Maryland, ||University of Padova, Italy

b.16. Deformation in the N = 82 Region (S. J. Freeman,* C. J. Lister,* P. Chowdhury,*B. Crowell,* D. J. Blumenthal,* C. N. Davids, B. B. Back, T. Lauritsen, K. S. Bindra,† W. Chung,‡ D. J. Henderson, and F. Soramel§)

Neutron-deficient $^{202,203,204}Rn$ nuclei were produced with the $^{27}Al + ^{181}Ta$ reaction at 132 and 150 MeV. At the target, X and gamma rays were detected in the Yale Compton Polarimeter, in coincidence with Rn recoils identified by mass at the FMA focal plane. The Polarimeter consists of four 6%-efficient unsuppressed germanium crystals. Using FMA-gamma coincidences it was possible to eliminate the fission, radioactivity, and Coulomb excitation backgrounds in the gamma spectra, allowing clean identification of the first few excited states in these nuclei as well as characteristic Rn Xrays. This preliminary experiment has demonstrated clearly the high resolving power and excellent background suppression of the FMA for reactions in this mass region. It is planned to use the Argonne-Notre Dame Compton-Suppressed array of Ge detectors to search for a region of predicted deformation in the light actinides. The use of the FMA should allow detection of channels where the fusion cross-section approaches the 0.1 mb level.

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*Yale University, †Resident Graduate Student from Vanderbilt University, ‡University of Notre Dame, §University of Padova, Italy

C. ACCELERATOR MASS SPECTROMETRY (AMS) AND SECONDARY BEAMS

Research with AMS concentrates on projects that utilize some of the unique properties of ATLAS: (i) the possibility to start with negative or positive ions from the tandem or ECR-PII injectors, respectively, the latter allowing us to perform experiments with noble gas radioisotopes; (ii) acceleration to high energies needed for removing isobaric background by fully stripping in the A ~ 60 mass range; and (iii) acceleration of ions from the whole periodic table to energies sufficiently high to perform isobar separation with the gas-filled magnetic spectrograph.

The first measurement of 76,000-yr ^{59}Ni in lunar surface material was accomplished with the fully-stripping technique. This opened the long-sought possibility to measure the integral flux of solar cosmic-ray alpha particles over the past ~ 200,000 years via the accumulation of ^{59}Ni produced by the ^{56}Fe$(\alpha,n)^{59}$Ni reaction.

The noble gas radioisotope project using the ECR source led to the first measurement of 269-yr ^{39}Ar in atmospheric argon, at the extremely low level of 1×10^{-15}. Here, the gas-filled magnet technique developed at Argonne was used. This result is encouraging for measurements of 210,000-yr ^{81}Kr with the same method, which is of interest for dating of deep ice cores from Greenland and Antarctica.

The heaviest radioisotope under consideration for AMS is 15-Myr ^{205}Pb, whose natural abundance in the thallium mineral lorandite ($TlAsS_2$) has been proposed as a means to study the pp solar neutrino flux in the past. The AMS technique will be developed with 2.2-day ^{203}Pb produced via ^{197}Au$(^{9}$Be,3n$)^{203}$Bi$(\beta^-)^{203}$Pb.

Accurate half-lives are the backbone of dating experiments. We have started a project to determine the ^{44}Ti half-life, which is of particular interest in connection with a possible detection of ^{44}Ti in supernova remnants by space-based gamma-ray spectrometers.

The secondary-beam project aims towards studying the reaction H$(^{17}$F$,^{14}$O$)^{4}$He which is of interest in connection with "hot" nucleosynthesis in stars. The 64-sec ^{17}F beam is produced half-way through ATLAS with the H$(^{17}$O$,^{17}$F$)$n reaction using a solid hydrogen target in the form of polypropylene. Extensive tests with a rotating target were performed.

a. Measurement of ^{59}Ni in Extraterrestrial Matter (W. Kutschera, I. Ahmad, B. G. Glagola, R. C. Pardo, K. E. Rehm, D. Berkovits,* M. Paul,* J. R. Arnold,† and K. Nishiizumi†)

It is known[1] that ^{59}Ni could serve as a monitor - perhaps the only one - for solar cosmic-ray alpha particle fluxes in the past. This 76,000-year radionuclide can be produced via the ^{59}Fe$(\alpha,n)^{59}$Ni reaction in a suitable target exposed for long time periods in space. A necessary requirement of the target is a high Fe content together with

*Hebrew University, Israel, †University of California San Diego, [1]L. J. Lanzerotti et al., Science 179, 1232 (1973), [2]W. Kutschera et al., Nucl. Instrum. Methods 73B, 403 (1993).

a low Ni and Co concentration, the latter to prevent production of ^{59}Ni through reactions by the much more abundant cosmic-ray protons ($p/\alpha \sim 100$). A measurement of the ^{59}Ni concentration on the surface of the moon is considered to be the best possibility to obtain information on the integral alpha-particle flux over the past ~ 200,000 years. We measured[2] the ^{59}Ni concentration in a 0.5-mm-thick surface layer of Apollo 16 lunar rock 68815. The measurement was performed with the tandem-ATLAS system at 641-MeV beam energy. At this energy it was possible to strip ^{59}Ni with 10% efficiency to bare 28^+ ions, thus separating it cleanly from ^{59}Co background in the split-pole magnetic spectrograph since Co can only acquire a maximum charge of 27^+ (see Fig. I-19). The ^{59}Ni concentration was determined from a $^{59}Ni/Ni$ ratio measurement of $(8.8 \pm 3.3) \times 10^{-13}$, where a known amount of Ni carrier was added in the chemical extraction of Ni from the lunar material. The resulting concentration is $(2.4 \pm 0.9) \times 10^{-14}$ g ^{59}Ni/g rock. This compares well with the ^{59}Ni production calculated by R. C. Reedy (Los Alamos) assuming an alpha particle flux spectrum similar to the one measured with satellites from solar flares over the past few years. This result indicates that no major change of the solar alpha-particle flux occurred in the past 200,000 years.

In the same experiment, a $^{59}Ni/Ni$ ratio of $(2.3 \pm 0.4) \times 10^{-11}$ was measured in a sample from the Admire stony-iron (pallasite) meteorite. Here the production proceeds mainly through the $^{58}Ni(n,\gamma)^{59}Ni$ reaction with the secondary neutrons originating from spallation processes with high-energy galactic cosmic-ray protons.

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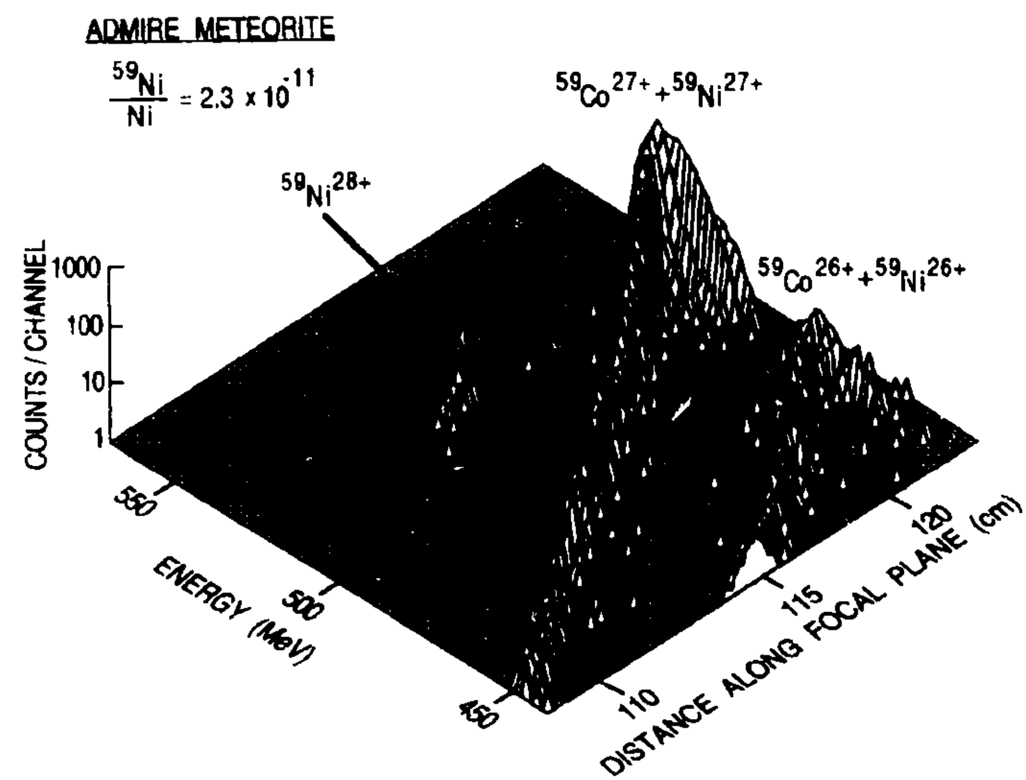

Fig. I-19. Separation of ^{59}Ni from ^{59}Co background by full stripping and detection in the split-pole magnetic spectrograph. The $^{59}Ni/^{59}Co$ ratio is approximately 1/1000.

b. **<u>First Detection of ^{39}Ar with Accelerator Mass Spectrometry</u>** (W. Kutschera, I. Ahmad, P. J. Billquist, B. G. Glagola, R. Harkewicz, R. C. Pardo, K. E. Rehm, and M. Paul*)

Accelerator mass spectrometry (AMS) is usually performed with tandem accelerators that require the formation of negative ions. Since noble gases do not form stable negative ions, it is not possible to measure their long-lived radioisotopes, ^{39}Ar ($t_{1/2}$ = 269 yr), ^{81}Kr (210,000 yr), and ^{85}Kr (10.7 yr), with tandem-based AMS. A few years ago, we suggested[1] that ECR sources coupled to heavy-ion accelerators might provide favorable conditions for AMS of noble gases starting with positively-charged ions.

Noble gas radionuclides are of considerable interest because, basically, their geophysical and geochemical behavior is easier to understand than those of reactive elements. ^{39}Ar and ^{81}Kr, which are produced by cosmic-ray interaction in the atmosphere, would be useful for measurements in the hydro- and cryosphere, e.g. dating of groundwater and ice cores. Present-day atmospheric ^{85}Kr (a fission product) is entirely man made since it originates from releases of nuclear fuel reprocessing. It could be useful as a tracer for noble gas kinetics on earth.

We report here on the first detection of cosmogenic ^{39}Ar with AMS using the ECR-ATLAS system in conjunction with the gass-filled split-pole spectrograph.[2] In order to accelerate $^{39}Ar^{8+}$ ions, the entire system from the ECR source to the spectrograph was tuned with a $^{78}Kr^{16+}$ pilot beam. The mass/charge ratio of these ions is the same as that of $^{39}Ar^{8+}$ within 0.01%, which makes them identical for all practical purposes of acceleration and beam transport. For the measurement of ^{39}Ar, the gas-filled spectrograph was used to separate ^{39}Ar from background ions of the ^{78}Kr pilot beam and the ^{39}K stable isobar. The efficiency of detecting $^{39}Ar^{8+}$ ions emitted from the ion source was about 2.5%. The ^{39}Ar isotopic abundance was measured by comparing the ^{39}Ar counting rate in the spectrograph with the $^{40}Ar^{8+}$ current at the ion source.

Samples consisted of about 100 cm^3 STP argon in quartz ampules. With oxygen as carrier gas and argon fed into stage II of the ECR source, a steady source output of 10 to 11 eμA of $^{40}Ar^{8+}$ ions was achieved. Several neutron-activated argon samples were prepared, with $^{39}Ar/Ar$ ratios ranging from 10^{-13} to 10^{-11}. This is substantially higher than the natural $^{39}Ar/Ar$ ratio, which is known to be 8.1×10^{-16} from low-level beta counting.[3] Figure I-20 shows focal-plane position spectra from various samples measured with a position-sensitive PPAC-Bragg-curve detector.[4] The spectra are cleaned up by gating on the ^{39}Ar region in the range vs energy parameter space measured in a Bragg-curve detector following the PPAC.

The extremely low cosmogenic $^{39}Ar/Ar$ ratio and the relatively short half-life of ^{39}Ar would require further increase in overall efficiency (^{39}Ar atoms detected per ^{39}Ar atom in the sample) to give AMS a significant advantage over state-of-the-art low-level ß counting. More promising for AMS is ^{81}Kr with its 2.1×10^5 yr half-life and a cosmogenic $^{81}Kr/Kr$ ratio of 5×10^{-13}. We plan to attempt AMS measurements of this radionuclide in the near future.

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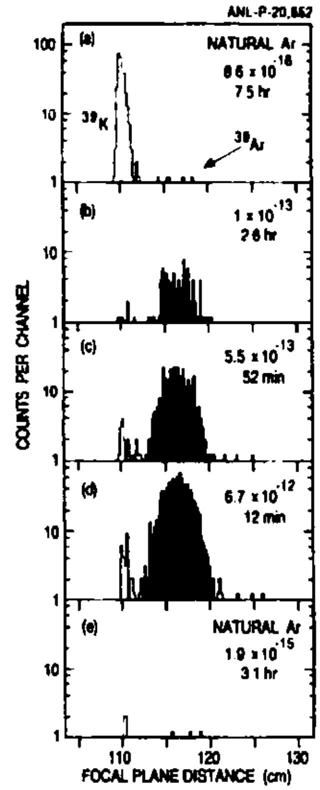
*Hebrew University, Israel, [1]W. Kutschera et al., Nucl. Instrum. Methods <u>B42</u>, 101 (1989), [2]M. Paul et al., Nucl. Instrum. Methods <u>A227</u>, 418 (1989), [3]H. H. Loosli, Earth & Planet, Sci. Lett. <u>63</u>, 51 (1983), [4]K. E. Rehm and F. L. H. Wolfs, Nucl. Instrum. Methods <u>A273</u>, 262 (1988).

Fig. I-20. Position spectra of 232-MeV ^{39}Ar ions from different argon gas samples measured in the focal-plane detector of the gas-filled split-pole spectrograph. The spectra are labeled by the measured $^{39}Ar/Ar$ ratio and the counting time, respectively. The spectra were measured in chronological order from a) to e).



c. <u>On the Use of ^{203}Pb for AMS of ^{205}Pb</u> (W. Kutschera, I. Ahmad, and M. Paul*)

Neutrinos from the primary hydrogen burning reaction in the sun, $p + p \rightarrow d + e^{+} + \nu$ ($E_{\nu} < 0.42$ MeV), were detected recently in the radiochemical detectors of GALLEX and SAGE. This indicates that the basic process of energy production is operational in the present-day sun at approximately the expected level.

It has been suggested that the accumulation of 15-Myr ^{205}Pb produced by the $^{205}Tl(\nu,e^{-})^{205}Pb$ reaction in a suitable thallium mineral could yield information about the pp solar-neutrino luminosity in the past. The threshold energy of neutrino capture in ^{205}Tl is 0.053 MeV, which makes this system particularly sensitive to pp neutrino reactions.

One of the many tasks in such a geochemical solar-neutrino experiment is the detection of ^{205}Pb at $^{205}Pb/Pb$ ratios around 10^{-14}. AMS is envisioned as one possible solution to this problem. A particularly difficult problem in such a measurement is the separation of ^{205}Pb from the isobaric background of ^{205}Tl. In addition, it is important to avoid as much as possible the use of artificial ^{205}Pb, in order to reduce the risk of building up laboratory contamination. We therefore developed a scheme to test all essential aspects of such an AMS measurement with the isobar pair ^{203}Pb - ^{203}Tl. For this purpose 2.2-day ^{203}Pb is produced by a suitable nuclear reaction.

*Hebrew University, Israel

The reaction $^{197}Au(^{9}Be,3n)^{203}Bi(\beta^{-})^{203}Pb$ was found to be an efficient way to produce ^{203}Pb. Irradiating a thick gold foil with 42-MeV ^{9}Be, resulted in a ^{203}Pb production rate of 1.3×10^{10} atoms/μAh. Samples for AMS with $^{203}Pb/Pb$ ratios in the range of 10^{-11} to 10^{-14} will be prepared by chemically extracting ^{203}Pb and mixing it with stable Pb. It is planned to pursue AMS of ^{203}Pb with the ECR-ATLAS system and the gas-filled spectrograph using this method.

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

The half-life of ^{44}Ti was measured several times in the past, but with conflicting results. Values reported in the literature are: 46.4 ± 1.7 yr (1965), 48.2 ± 0.9 yr (1965), 54.2 ± 2.1 yr (1983), 66.6 ± 1.6 yr (1990). There is considerable interest in a more accurate half-life because ^{44}Ti may become detectable as a long-lived gamma-ray activity from the remnant of supernova SN1987A, when the shorter-lived activities (e.g. 77-day ^{56}Co) have died away. To determine the initial ^{44}Ti production, the half-life must be known.

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 intensity of the 1157-keV gamma line from the ^{44}Ti decay (actually the decay of the short-lived daughter ^{44}Sc) is measured relative to the close-lying 1173-keV gamma line of ^{60}Co. Since the half-life of ^{60}Co is very well known, 5.271 ± 0.001 yr, an accurate result should be obtainable following the decay for a few years. Three mixed sources containing 200 nCi ^{44}Ti and 200 nCi ^{60}Co each, and three pure ^{60}Co sources with 300 nCi each, were prepared. A set of a mixed and a pure source was given to two other laboratories (Hebrew University Jerusalem, CNR Torino).

The goal of this project is to have three independent measurements performed over a few years, and then compare the results. It is expected that this procedure will lead to an accurate determination of the half-life of ^{44}Ti.

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* Istituto di Cosmogeofisica, CNR Torino, Italy

† Hebrew University, Israel

e. **Secondary Beam Development with Inverse Kinematic Reactions** (W. Kutschera, J. P. Greene, R. C. Pardo, K. E. Rehm, J. P. Schiffer, D. Berkovits,* M. Paul,* and T. F. Wang†)

Beams of short-lived (≤ 1 hr) radionuclides are of particular interest for studying reactions relevant to nucleosynthesis in so-called "hot" stellar matter. Qualitatively, this is a region were particle reactions on short-lived radionuclides start to compete with beta decay. Since targets of short-lived radionuclides are impractical, beams of these nuclides are required.

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* Hebrew University, Israel

† Lawrence Livermore National Laboratory

We pursue an approach where a beam of 64-sec ^{17}F is produced half-way through ATLAS with the reaction $H(^{17}O,^{17}F)n$. The goal is to obtain enough intensity to study the secondary-beam reaction $H(^{17}F,^{14}O)^{4}He$ with the split-pole magnetic spectrograph. The inverse of this reaction, $^{14}O(\alpha,p)^{17}F$ mediates the "break-out" from the hot CNO cycle. It was suggested that a measurement of the cross section at an equivalent alpha-particle energy of 2 MeV (sigma ~ 0.5 mb) will give valuable information to extrapolate to the interesting region of stellar temperatures around 5×10^{8} degrees Kelvin.

The major technical challenge for the production of a ^{17}F beam with sufficient intensity (10^{6} to 10^{7} pps), is a hydrogen target that can withstand a primary ^{17}O beam of high brilliance (~ 1 pμA/mm^{2}). To this end, we have developed and tested a rotating target with Al-coated polypropelene foils, $(CH_2)n$. Compared to stationary foils a beam increase of a factor 100 was achieved (1 to 100 pnA). The deceleration and transport of the ^{17}F beam has been investigated in detail by computer simulations with a raytrace program. These simulations showed that, provided the high brilliance of the primary beam can be achieved, the concept of a ^{17}F beam should be feasible. This program will be pursued with the goal of measuring the cross section of the above-mentioned 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 beams of charged particles contained in storage rings or ion traps. First experiments involving Li beams at the Aarhus storage ring ASTRID have been analyzed.

a. **Measurements at ASTRID** (J. S. Hangst,* P. S. Jessen,† M. Kristensen,† J. S. Nielsen,† P. Shi,† O. Poulsen,† and J. P. Schiffer)

Further data were obtained at the small storage ring ASTRID, with the capability of laser cooling ion beams, in Aarhus, Denmark. The analysis of the data with laser-cooled $^7Li^+$ beams, of beam size measurements, measurements of the Schottky signals from such beams, and of the observed laser-induced fluorescence has been completed. After injection of a 100-keV $^7Li^+$ beam into ASTRID, evidence was found in the first second for an initial resonant growth of beam oscillations and associated beam loss, during which laser cooling was ineffective. Measurements of the laser fluorescence indicate a gradual increase in the longitudinal temperature, presumably associated with transverse-longitudinal coupling and equilibration with the injected (longitudinally cold and transversely hot) beam. The vertical size of the equilibrated beam is large (on the order of cms). Once the beam has been equilibrated it apparently can be longitudinally cooled very effectively; this is attributed to the weak coupling within the rather diffuse beam.

The $^7Li^+$ measurements were hampered by the fact that only a small fraction (about 10^{-4}) of the beam is in the isomeric state that may be addressed by the laser light. The first measurements utilizing a transverse laser were also obtained. The transverse velocity distribution of the beam was measured directly and found to be in good agreement with earlier scraper measurements. The transverse beam temperature increases rapidly after injection, indicating the presence of an instability in the dense ASTRID beam. No evidence for transverse laser cooling was observed. This was expected due to the short physical overlap between the laser and ion beams.

A measurement with $^{24}Mg^+$, where 100% of the beam should communicate with the laser is planned for the coming year.

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* Supported in part by the Danish Research Academy, †University of Aarhus, Denmark

b. **Phase Transitions in Cold Ionic Systems** (J. P. Schiffer)

Simulations have been carried out of ions confined in anisotropic, but axially symmetric fields, approximating configurations that have been attained in ion traps in the laboratory. Two limits have been explored for a harmonic force. When the axial field is weak compared to the one responsible for the equatorial confining force, ions will be squeezed by the equatorial force to align themselves in a linear configuration along the axis. At a certain value of the ratio of the axial to the equatorial force the configuration changes from one-dimensional to 2-dimensional, with the central ions forming a planer zig-zag configuration as shown in Fig. I-21. At a somewhat lower value of this ratio the zig-zag pattern twists out of the plane into the 3rd dimension; The transition is illustrated in Fig. I-22. And finally, in the limit where the axial force is much stronger than the equatorial, the ions are flattened onto the mid-plane in a 2-dimensional disk. The ratios in the fields at which these dimensional phase transitions occur depend on the number of confined ions, with a simple numerical relationship that has been determined empirically.

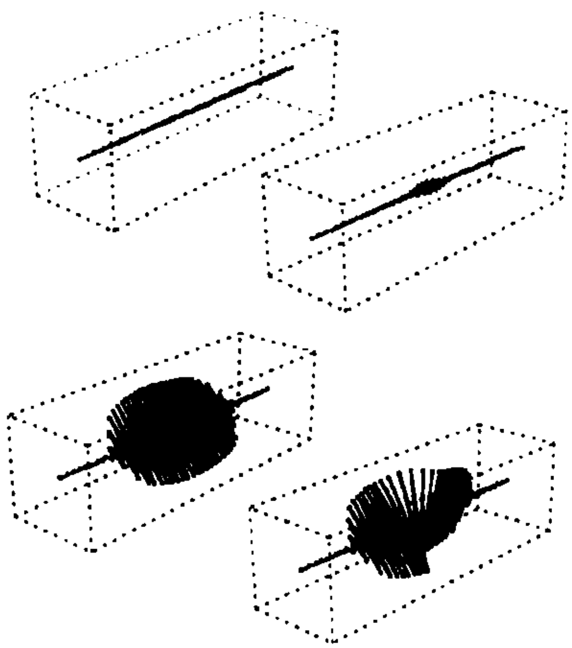

Fig. I-21. Minimum-energy configurations of 70 ions with the asymmetry in the confining potential α = (1.52, 1.56, 2.17, and 3.13) × 10⁻³. The scales in the x and y directions are expanded by a factor of 100 with respect to that for the z axis.

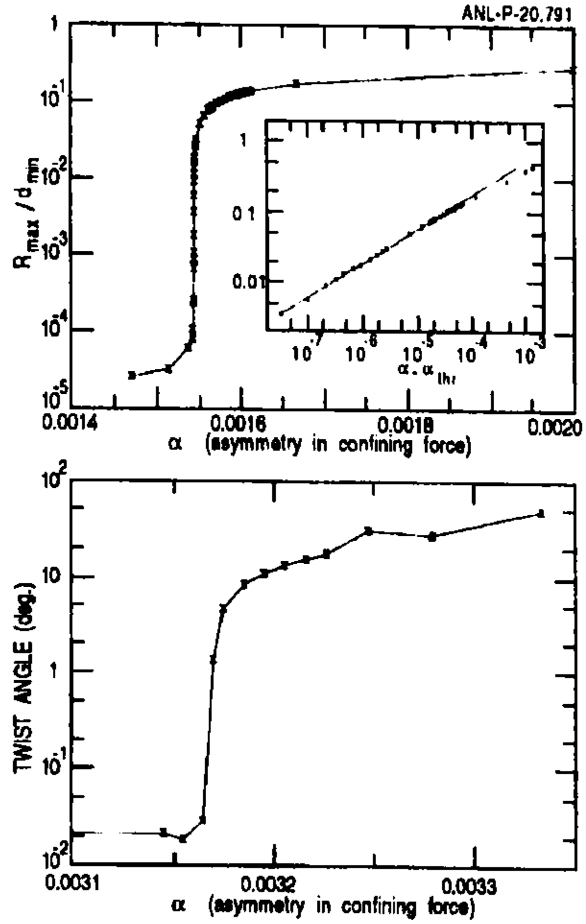

Fig. I-22. The maximum radius $(x^2 + y^2)^{1/2}$ (divided by the least spacing along the z axis) as a function of the asymmetry α in the confining potential is shown in the top panel. The inset shows the same quantity plotted logarith mically for the asymmetry above the apparent threshold value, and showing a square-root threshold behavior. The lower panel shows the angle by which the zigzag pattern shifts out of a planar configuration.

c. **Recoil-free Scattering of Light and Other Low-Temperature Limits in Cold Confined Ionic Systems** (J. P. Schiffer)

There are several limits of interest in low-temperature confined ionic systems. One question is the temperature at which it should become possible to observe diffraction effects in the scattering of laser light from order in the confined ions. The distances are large (typically tens of microns) and the temperature at which a typical photon could be absorbed in a recoil-free manner is very low (1' µK or lower). However, to satisfy the Bragg condition in low orders, the scattering of photons involves much smaller momentum transfer and thus coherent, recoil-free scattering may take place at much higher temperatures. In fact, the scattering should be largely recoil free at any temperature at which the system becomes ordered. Estimates have also been made of the temperature at which quantum effects may start becoming important, obtaining an effective 'Debye temperature' for confined ionic systems; these estimates are shown in Fig. I-23.

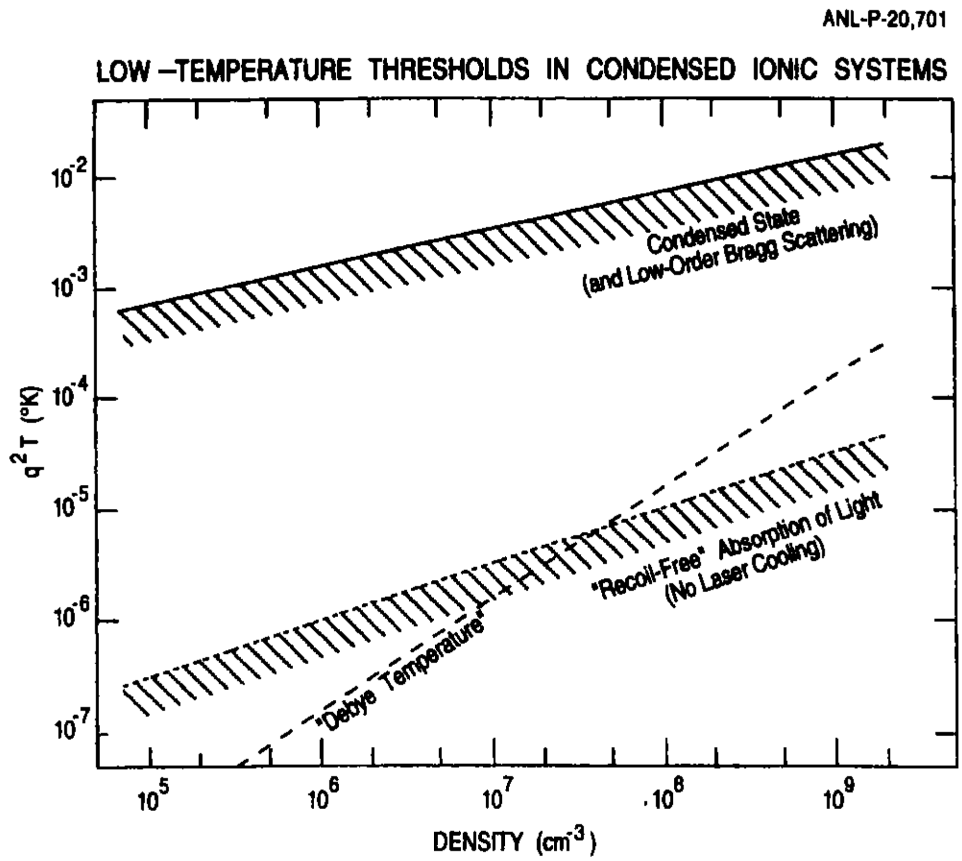

Fig. I-23. Plot of estimates for threshold temperatures (times q^2) at which various phenomena may be expected to begin to play a role for singly-charged ions. The lines correspond to the nominal condensation point, the estimate of a "Debye temperature" for ^{24}Mg (dashed) and the recoil-free absorption limit for 500 nm light (dotted).

d. **Nuclear Structure Studies Using Radioactive Beams and Inverse Kinematics** (G. Kraus,* P. Egelhof,* B. Franzke,* H. Geissel,* A. Gruber,* A. Magel,* G. Münzenberg,* F. Nickel,* K. Sümmerer,* A. Weiss,* D. Viera,* M. Hamm,† J. V. Kratz,† J. Friese,† A. Gillitzer,† H. J. Körner,‡ M. Peter,‡ W. Henning, J. P. Schiffer, L. Chulkov,§ M. Golovkov§, and A. Ogloblin§)

An experiment was carried out at GSI to both test the feasibility of obtaining nuclear structure information from reactions in inverse kinematics, and to measure the poorly known matrix element for the first-excited 2.7-MeV state of the doubly-closed-shell nucleus ^{56}Ni.

A beam of 101-MeV/u ^{56}Ni from the GSI fragment separator was focussed onto a 1-mg/cm^2 CH_2 target, perpendicular to the beam. The scattered protons were detected in an annular ring of Si detectors that covered the angular range between 78 and 83 degrees in the laboratory. For the inelastic scattering this corresponds to 12 to 18 degrees in the center-of-mass, which is the region where the first diffraction maximum occurs in the angular distribution. The kinematics of the reaction are such that the inelastic protons are separated in energy from the elastic, even though the beam energy resolution is rather poor (around 2%). The beam particles, up to 10^5/sec, were tracked by two position-sensitive scintillation counters. The inelastic cross section for exciting the 2.7-MeV 2^+ state of ^{56}Ni yields a value of $\beta_2 \approx 0.21$, while previous measurements set only a substantially lower lower limit. The technique was successful and further experiments are planned for the ESR storage ring, where better energy resolution and smaller beam spots should allow more difficult measurements to be carried out.

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e. **Electron Capture Decay of ^{231}U** (I. Ahmad, E. Browne,* K. E. Gregorich,* S. A. Kreek,* D. M. Lee,* D. C. Hoffman,* and R. W. Hoff†)

An attempt was made to produce ^{229}U activity in order to investigate the levels in the octupole-deformed nucleus ^{229}Pa. The experiment involved the irradiation of 8 properly-spaced thin ^{233}U targets with 50-MeV protons at the LBL 88-inch cyclotron and extracting the Np recoil products with a He jet system. The U atoms, which were produced from the decay of Np, were chemically purified and their gamma and conversion electron spectra were measured. Because of the intense ^{231}U activity, we could not observe any ^{229}U gamma rays. However, these measurements provided more precise intensities and log ft values for the electron capture decay of ^{231}U than the values obtained in previous measurements with a NaI detector. These data provide additional evidence for the single-particle assignments in ^{231}Pa.

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* Lawrence Berkeley Laboratory, †Lawrence Livermore National Laboratory

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 μ_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 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 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 an 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 dihedral 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 μ_e but much greater than 2 $\mu_e E$, and can be detected within the limitation imposed by the uncertainty principle. The phase shift can be detected as a shift in longitudinal 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 problems in principle which apply to this particular scheme. We have other schemes that we are considering as well as some possibilities of dealing with these questions of principle. In any of these cases one would want to try these ideas on a simplified test if possible before proceeding to a full-scale measurement. We believe such a test is possible using magnetic acceleration.

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* SSC Laboratory

E. EQUIPMENT DEVELOPMENT AT THE ATLAS FACILITY

The installation of the Fragment Mass Analyzer (FMA) was completed and the experimental program using this new device has started. About 50% of the latest experiment proposals requested the use of the FMA. For the mass resolution the excellent value of 525:1 was measured and beam attenuation ratios of 10^{-6}-10^{-11} were obtained. Many of the experiments make use of the Compton-suppressed Ge-detector array which allows us to mount 10 detectors from the ANL-Notre Dame Ge-detector array around the target chamber of the FMA.

In the APEX experiment the past year saw the completion of the final assembly of the apparatus and considerable progress toward the complete installation of the various detector systems was made. First experiments with ^{238}U beams from ATLAS, testing the beam properties (beam spot size, time structure) and parts of the detector system began. All detectors of the heavy-ion array were installed and tested with respect to their angle- and time-resolution. The two barrel-shaped NaI arrays are installed at APEX and efficiency, position- and energy resolution were measured. All Si detectors for the electron-positron- arrays were tested and one Si-array is installed at APEX. The cooling system was installed and first tests of the δ-electron rate from the reaction U+Au were performed. The electronics and the trigger processor are presently being installed at APEX and first tests of the system are planned for the spring of 1993.

In the GAMMASPHERE project the Physics Division has taken on the responsibility for procuring and testing of the BGO detectors, for the design and fabrication of the scattering chamber, and for part of the software development. The first BGO detectors were delivered from the two vendors starting in the fall of 1992. They are tested with respect to mechanical tolerances, energy- and time- resolution at Argonne and then shipped to LBL. A scattering chamber for the early implementation stage of GAMMASPHERE was built and is installed at Berkeley. For the GAMMASPHERE software several programs for event simulation, gain matching and gain drift corrections were developed.

Other development projects at ATLAS include the double-sided Si strip-detector array and first tests using the gas-filled magnet technique for fusion measurements at sub-barrier energies.

a. **Fragment Mass Analyzer Project** (C. Davids, B. Back, K. Bindra,* D. Henderson, T. Lauritsen, H. Penttilä,† and F. Soramel‡)

The FMA has been operating for about 1 year, and the results are very encouraging. Precise calibrations of the positions of ions at the focal plane showed that the 40° bending magnet needed to be shifted inward by 4.3 mm. When this was done, the central ion position fell in the desired location at the center of the focal plane. In addition, a small first-order position shift with energy that had always been present was now completely eliminated. The reason the magnet had to be moved lies with the extension of its fringe field. Particles begin to bend before they even enter the magnet, and as a result their paths do not coincide with the calculated orbits unless the magnet is moved closer to its center of curvature.

*Resident Graduate Student from Vanderbilt University, †Supported in part by the University of Maryland, ‡University of Padova, Italy

An experiment to measure the primary beam attenuation at the FMA focal plane was performed in collaboration with personnel from Legnaro National Laboratory in Italy. A beam of ^{58}Ni was used to bombard targets ranging in mass from 27 to 197. The results show that the beam attenuation ranged from 10^{-6} to 10^{-11}, the smallest values being obtained where the beam is lighter than the target. During this experiment a mass measurement of the fusion products in the system ^{58}Ni on ^{64}Ni yielded a mass resolution of 525:1, and a total efficiency of 24% with 2 charge states on the focal plane for mass 118. Even higher values for the efficiency are expected when 3 charge states are placed on the focal plane. Figure I-24 shows the mass spectrum.

Ten detectors from the Argonne-Notre Dame Compton-Suppressed Germanium detector array were installed around the FMA target position, and several experiments were performed. A small scattering chamber is used with this setup, containing a Si detector for beam monitoring, a motorized target ladder, and a second ladder for inserting charge-state resetting foils a few centimeters behind the target. It was found that if a reset foil at a distance of 30 cm from the target is used for slow heavy recoils, multiple scattering in this foil degrades the mass resolution at the focal plane.

The vacuum safety system for the FMA was installed. It divides the FMA into 3 zones, and allows full control of all pumps, valves, and vacuum gauges. Beamline valve status and pressure information is displayed by the FMA control computer.

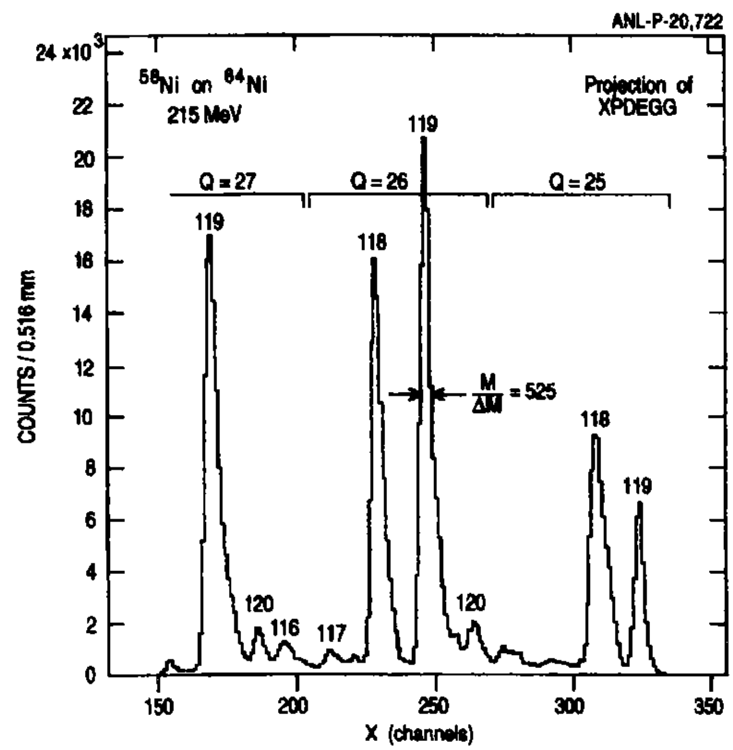

Fig. I-24. M/q spectrum at the FMA focal plane from the ^{58}Ni + ^{64}Ni reaction at 215 MeV.

b. **The ATLAS Positron Experiment (APEX)** I. Ahmad,[1] S. M. Austin,[2] B. B. Back,[1] D. Bazin,[2] R. R. Betts,[1] F. P. Calaprice,[3] K. C. Chan,[7] A. Chisti,[7] P. Chowdhury,[7] R. Dunford,[1] J. D. Fox,[4] S. Freedman,[1] M. Freer,[1] S. Gazes,[5] J. S. Greenberg,[7] A. L. Halllin,[8] T. Happ,[1] N. Kaloskamis,[7] E. Kashy,[2] W. Kutschera,[1] C. J. Lister,[7] M. Liu,[8] M. R. Maier,[2] A. Perera,[5] E. Roa,[4] M. Rhein,[1] J. P. Schiffer,[1] T. Trainor,[6] P. Wilt,[1] J. S. Winfield,[2] F. L. H. Wolfs,[5] M. Wolanski,[1] A. Wuosmaa,[1] and J. E. Yurkon[2]

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 are concerned, 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 will 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 covered effectively 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 collaboration involves 36 scientists including 6 graduate students.

The past year has seen completion of the final assembly of the apparatus and considerable progress toward the complete installation of the detector systems and their associated electronics. Tests of the functioning of APEX have been carried out using both sources and beams from ATLAS, including the first U beams from the newly completed positive-ion injector. In all cases, the performance of APEX has been found to be close to that envisaged in the original design. 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, 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.

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[1]Argonne National Laboratory, [2]Michigan State University, [3]Princeton University, [4]Florida State University, [5]University of Rochester, [6]University of Washington, [7]Yale University, [8]Queen's University

A number of experiments were performed at the FMA focal plane. High-spin microsecond isomers were studied by stopping the recoils on a foil behind the focal plane and observing the de-excitation gamma rays in Ge detectors. The moving tape collector (Iowa State, Maryland, and LSU) was tested, and after some modifications it will be ready for use in experiments. A test run on the production of $f_{7/2}$ nuclei needed for experiments with the nuclear spectroscopy/nuclear moments facility behind the focal plane (Rutgers, Weizmann) showed encouraging results.

H. Penttilä from the University of Jyväskylä in Finland arrived to work on the FMA in a postdoctoral position. He is jointly funded by ANL and the University of Maryland. Graduate student K. Bindra (Vanderbilt University) continues to conduct his Ph.D research on the FMA. W. Chung (University of Notre Dame) returned to his home institution.

The commissioning of the FMA already involves many outside users from Purdue, Notre Dame, Vanderbilt, Yale, Kentucky, Lawrence Berkeley Laboratory, and Oak Ridge National Laboratory. Additional users from Washington University, Rutgers, Edinburgh, Weizmann Institute, Tennessee, Australian National University, and Maryland will be involved in experiments already approved.

a.1 **Moving Tape Collector for the FMA Focal Plane** (J. C. Hill,* F. Wohn,* W. B. Walters,† E. F. Zganjar,‡ H. Penttilä,¶ A. V. Ramayya,§ and C. N. Davids)

The moving tape collector (Iowa State, Maryland, and Louisiana State) has been tested with ATLAS beams. Modifications are in progress which will allow the detector system to be placed off the central beam axis and shielded from background at the focal plane.

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*Iowa State University, †University of Maryland, ‡Louisiana State University, §Vanderbilt University, ¶Supported in part by the University of Maryland

a.2 **Nuclear Spectroscopy/Nuclear Moments Facility for the FMA Focal Plane** (N. Koller,* A. Mountford,* T. Vaas,* G. Goldring,† B. Zimmerman,‡ D. J. Henderson, and C. N. Davids)

A test run with the FMA to determine the production rate of ^{43}Ti and ^{45}V was performed, and encouraging results were obtained using ^{32}S and ^{35}Cl beams on a ^{12}C target. Work is now in progress on the installation of the NMR magnet and the vacuum system behind the FMA focal plane.

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*Rutgers University, †Weizmann Institute, Israel, ‡University of Tennessee

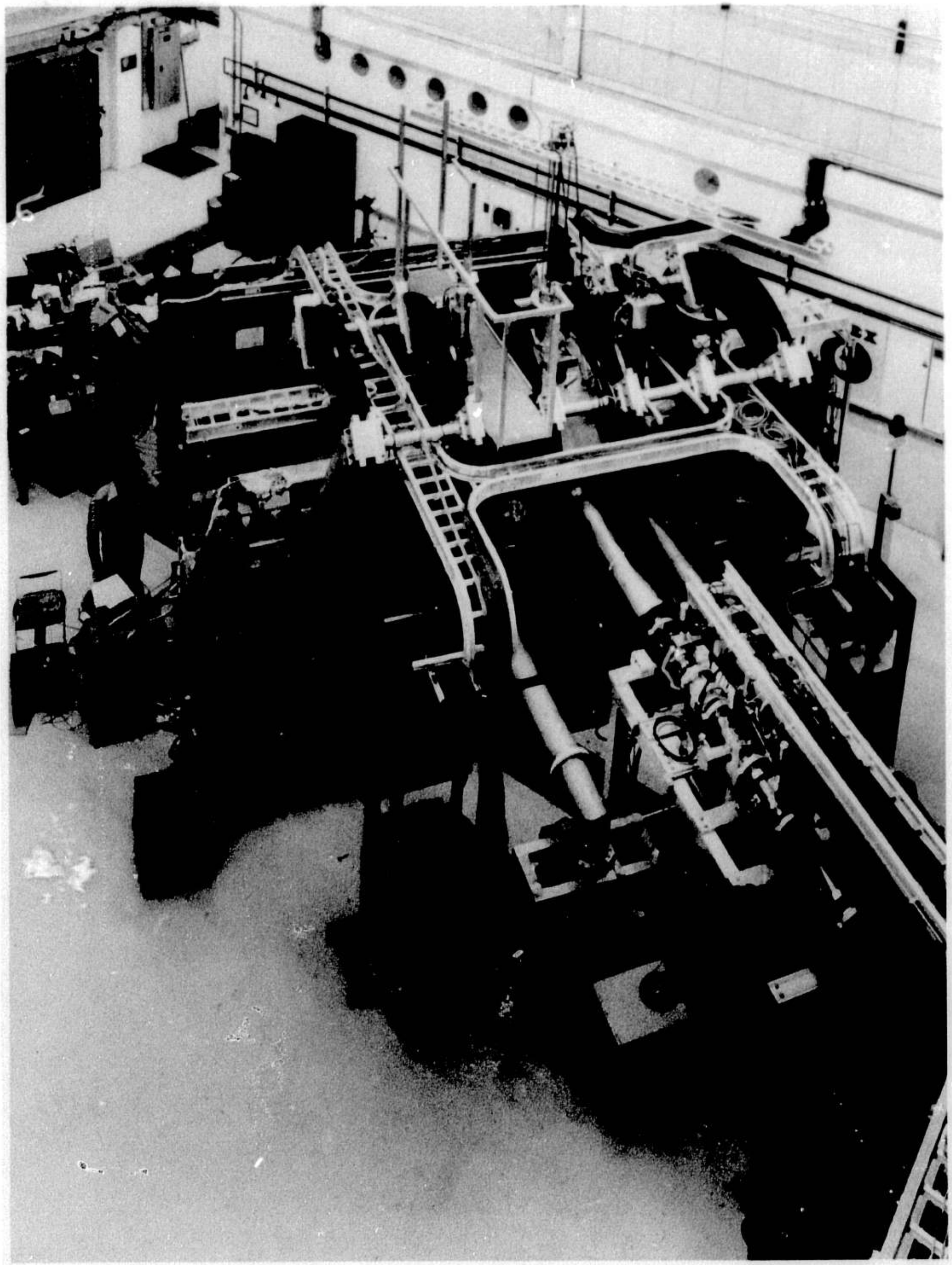

Fig. I-25. View of APEX in ATLAS Target Area IV. The beam line from ATLAS is in the lower right of the picture.

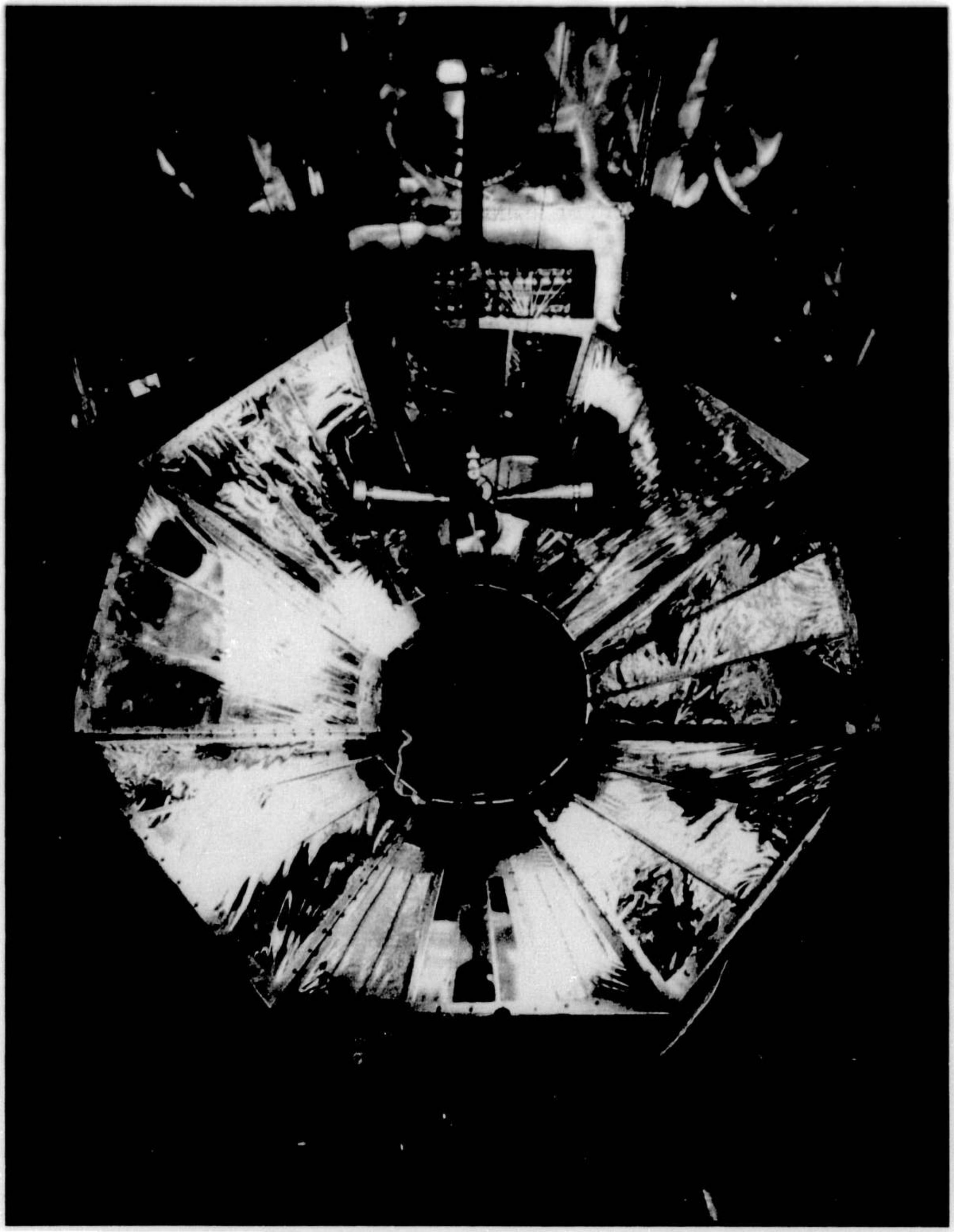

Fig. I-26. View inside the main vacuum chamber of APEX. The solenoid axis is horizontal. This picture, taken from below, shows the rotating target wheel positioned between the two electron/gamma stops. Behind is the large array of gas counters for heavy-ion detection. The beam enters from the upper left, passes through the target and exits through the center of the heavy-ion counter array.

Solenoid and Vacuum Chamber

The APEX solenoid and vacuum chamber, constructed at Princeton, has been in essentially complete form since summer 1991. During the past year we installed a number of items inside the vacuum vessel and completed an upgrade of the pumping and vacuum control systems. The mounting hardware for the large array of parallel-plate avalanche counters was installed and aligned, as were conical heavy-metal pieces suspended on the solenoid axis (electron/gamma stops) designed to absorb the intense flux of photons produced at the target and to intercept the prolific low-energy electrons which are emitted in collisions of very heavy ions. The alignment and functioning of the electron/gamma stops was verified using both gamma-ray and electron sources placed at the target position.

The vacuum system was improved and augmented by the replacement of the two original turbo-molecular pumps and by the addition of a cryopanel. Although the originally supplied turbo-molecular pumps performed well in producing a low base pressure in the APEX chamber, several bearing failures at critical times led us to replace the original pumps (surplus from the Princeton Plasma Physics Laboratory) with new pumps of more modern design and of higher reliability.

The vacuum control system, constructed using commercial programmable logic units was reconfigured and now includes, in addition to control of the chamber pumping systems, control of the cryopanel and isobutane systems for the various gas counter arrays in APEX. This system has proved extremely flexible and reliable in operation.

APEX Beamline

Following the replacement of the original quadrupoles with the type commonly used at ATLAS, very satisfactory transmission and focussing of rigid Ni beams from ATLAS was obtained. During September and October 1992, the first ^{238}U beams from ATLAS were transported to the target position of APEX. The size of the beam spot was measured using a viewing quartz and by measurement of the transmission through various sized apertures. A transmission of 75% through a 3-mm diameter aperture indicates a beam spot size roughly 3.5 mm in diameter. The time structure of the U beam was investigated using a small parallel-plate avalanche counter to measure the time spread of elastically scattered beam from a thin gold target. A time spread of 1 ns was measured for an unbunched beam and this was easily improved to <500 ps using the (not optimally positioned) rebuncher at the exit of ATLAS.

Target Assembly and Targets

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 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. This assembly was fabricated at Florida State University. 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 intersects the beam path. 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 wheel angle is computer controlled. The target assembly was used in the non-rotating mode during the several beam tests carried out in 1992. The electronic control for the beam-chopping mechanism is in place and the correct phasing of the wheel was demonstrated using stroboscopic viewing with a light triggered by the output of the beam-chopping electronics. The vacuum transfer mechanism has been used extensively for both target and source changes and has proved easy and convenient to use.

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

Monitor Detectors

A variety of detectors for monitoring the beam position, target quality, energy spread and timing of the beam have been constructed at the University of Washington.

Two high-resolution ion chambers are used to measure the energy spread of the elastically scattered beam. Initial results indicated <0.75% energy resolution for 5.3-MeV/u ^{238}U when scattered from a Au target with a thickness corresponding to an energy loss of 16.5 MeV (1.3%). These detectors will provide important information on target degradation which is expected to be reflected in an energy "tailing" of the elastic-scattering peak.

A small, thin parallel-plate avalanche counter, placed in front of one of the ion chambers, serves to determine the time spread of the pulsed beam from ATLAS. This detector was used in the bunching tests referred to in the "Beamline" section. It is estimated that this detector has an intrinsic time resolution of ~ 40 ps for 6-MeV/u U due mainly to the large signal generated by these heavily ionizing particles.

Lastly, a set of four CsI scintillators read out with photodiodes and mounted symmetrically above and below, and left and right of the beam axis are used to measure the stability of the beam position on target.

Heavy-Ion Array

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. They have been designed and constructed at Michigan State University.

The full array is installed in APEX and connected to the gas-handling system which is interfaced with the vacuum control system. A number of tests were carried out over the past year. In the first of these, Mott scattering of ^{58}Ni + ^{58}Ni at sub-Coulomb energies was measured. These data show the oscillations characteristic of the interference of forward and backward scattering amplitudes for identical bosons. The resolution of these oscillations, calculated to have a period of 1.4°, indicates an angular resolution of a few tenths of a degree for the counters. More recently, scattering of ^{238}U from ^{181}Ta, ^{197}Au and ^{238}U was measured. Analysis of these data indicates a mass resolution of ≈5 u, close to that expected from our simulations of the various contributions to the experimental resolution. The final configuration of the electronics for the heavy ion array was installed.

Sodium Iodide Array

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. 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.

Both arrays and their associated electronics are now installed at APEX. Numerous measurements of the energy and position resolution of the arrays were made using positron sources. The total efficiency of the array was also determined. All these values ($\Delta E \approx 15\%$, $\Delta \approx 3$ cm and $\varepsilon \approx 28\%$) are close to the design values. The arrays were interfaced with the trigger processor and we have successfully combined the annihilation-radiation detection with positron detection in the silicon array. The identification of beam-produced positrons has been demonstrated.

Silicon Detector

The APEX experiment contains two arrays of silicon detectors positioned on the solenoid axis. Each array consists of 216 silicon detector elements, 3×0.5 cm^2 arranged on the surface of a hexagonal cylinder. These detectors provide information on the energy, time-of-flight, and impact position of positrons and electrons which strike the array after spiralling down the solenoid.

The detectors are configured with three active elements on a trapezoidal wafer mounted on a ceramic substrate. The wafers are mounted on hexagonal rings which are in turn mounted on a G-10 rod. The whole assembly is contained in an aluminized mylar shroud and cooled to -80°C by flowing cold nitrogen gas at 100 torr pressure over the detectors.

All the detectors were delivered and tested. Both arrays are mechanically complete and one was fully loaded with detectors and installed in APEX. Tests with sources placed in the target position were made to align the array with the solenoid field, which, to compensate for the earth's magnetic field, requires a displacement and tilting of the array relative to the geometric axis of the solenoid.

The cooling system was tested with the array and a temperature of -80°C was achieved. Installation of the final electronics for the silicon array have now been installed.

Several tests of the silicon array were carried out using subsets of detectors during the first U-beam times. The rate of δ-electrons reaching the array was measured for U + Au at 5.5 MeV/u and was found to be close to that calculated from measured δ-electron production cross-sections. Also many tests were conducted using electron sources. The first tests with positron sources and integration with the annihilation detector array were carried out in February 1993, followed by a test run measuring beam-produced positrons.

Electronics

All of the commercial electronics were received and tested and are now 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 was designed, built, tested, and produced for APEX by LeCroy. All modules were delivered.

An 8-channel shaping module was designed and evaluated. A low-level discriminator circuit and hit-pattern output will be incorporated in this design. These modules were produced by a commercial board house and were delivered, and their installation is proceeding.

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 complete.

A "motherboard" assembly for mounting the silicon preamps, containing all control and monitoring circuitry was designed and fabricated.

A "Peak-to-FERA" module to allow the use of FERA ADC's with silicon detectors was developed. It is being produced by LeCroy for APEX.

All cables are installed and we are currently in the process of final installation and testing of electronics.

Trigger Processor and Data Acquisition

A trigger module for APEX was 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 is then used in combination with logic from the accelerator and other APEX detectors to generate the electronics and data-acquisition gates.

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 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 was written. A new VAX 4000 Workstation was purchased for the sole use of APEX data acquisition and analysis.

c. **GAMMASPHERE Activities at Argonne** (T. L. Khoo, M. Carpenter, I. Ahmad, J. Falout, T. Lauritsen, and S. Harfenist*)

A powerful third-generation 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 is essential for high- ($\geq$ 3) fold coincidences. Since each additional fold results in roughly an order-of-magnitude improvement in selectivity, this feature makes it possible to isolate cleanly weak structures, where new physics will undoubtedly lie. Since GAMMASPHERE represents a national facility, we are committed to participate in its construction. T. L. Khoo is the Chairman of the GAMMASPHERE Scientific Advisory Committee (formerly Steering Committee) which follows, and provides advice on, the construction of GAMMASPHERE. R. V. F. Janssens is Chairman of the Users Executive Committee.

Through our activities in R&D, planning committees, and the Steering Committee, ANL has played a major role in securing funding for the project and in defining the instrument. Now, with the project in the construction phase, we are vigorously participating in GAMMASPHERE construction, at a level of larger than 2 FTEs. We are responsible for: (i) all aspects of the BGO detectors, including specifications, design, procurement, testing and mechanical verification; (ii) a substantial portion of the front-end VME software, including all aspects which involve Ge and BGO detector parameters (calibration, trapping corrections, threshold levels, etc.), as well as event simulation and user interface; (iii) target chambers for both the early implementation phase (consisting of 30 Compton-suppressed spectrometers) and the final phases.

All BGO detectors due by January 1993 were received at Argonne. Testing revealed that almost all detectors meet performance specifications. The hexagonal detectors come very close to conforming to our very demanding mechanical specifications, with the latest detectors received now fully conforming after frequent interactions with the manufacturers. The early implementation target chamber was delivered to LBL on schedule. Software effort was delayed due to staff changes, but has picked up vigorously with the assignment of T. Lauritsen to this task. Earlier Argonne 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 mea urements 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; and (vii) participating in writing the GAMMASPHERE Baseline Review Document (May 1991) and the GAMMASPHERE functional requirements, which define the capabilities of the instrument. A paper on Compton-suppressed spectrometer performance has been published.

*Science Engineering Research Semester Student, Buffalo State College

c.1 Testing of the BGO Compton-Suppression 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. The bismuth germanate (BGO) Compton-suppression detector system for each Ge detector consists of one tapered hexagonal BGO side shield and one slotted BGO back plug. Due to the geometry of the array, three types of annular shields are required. These types are referred to as B, C and D and the array will consist of 60, 30 and 20 of these units, respectively. Shield types B, C and D have a hexagonal geometry. They are divided into six optically separate sections, each with its own pair of photomultiplier tubes.

Argonne took responsibility for the procurement and testing of the BGO Compton-suppression units. At present, we received 13 B-type, 13 C-type and 26 backplug detectors from the two vendors. All of these detectors were delivered to ANL for testing. However, testing of detectors will soon begin at two universities, namely Stony Brook and Yale. A set of test procedures was developed in order to insure that all units meet the required mechanical and performance specifications. For the most part, all crystals meet or exceed the performance criteria established previously. Those which do not meet these criteria have problems with either energy resolution or uniformity.

In order that the BGO detectors operate as efficient Compton suppressors for events in which a photon undergoes multiple scattering, the lower level discriminator threshold must be set around 10 keV for each segment. A typical low-energy response of one BGO segment to a 59.5 keV γ ray is shown in Fig. I-27 as measured with a ^{241}Am source. The 45:1 peak-to-valley ratio (P/V) obtained for this segment is excellent and will allow discriminator levels to be adjusted below 10 keV. All of the segments measured to this date exceed the 10:1 specification on the P/V ratio and in most cases are above 30:1.

In order to test all of these detectors in a timely fashion, we upgraded our detector laboratory with the installation of a CAMAC-based acquisition system. This system consists of a list sequencer and ethernet crate controller which are both manufactured by Hytec. This system was integrated with DAPHNE allowing us to take multiparameter data and fill histograms.

c.2 Target Chambers for GAMMASPHERE (M. P. Carpenter, J. Falout, I. Ahmad, R. V. F. Janssens, and T. L. Khoo)

As one of our responsibilities for GAMMASPHERE, we took on the task of designing and constructing two target chambers and associated beamlines to be used with the spectrometer. The first chamber was completed and delivered to LBL. It will be used for approximately six months in conjunction with the early implementation support frame. The chamber consists of two spun-Al hemispheres welded together giving a wall thickness of 0.063 inches and a diameter of 12 inches. The top and bottom of the sphere were lopped off in order to take into account the geometry defined by the support. The flat surfaces at the top and bottom are fitted with lids, and the target is supported from the top lid. The total height of the chamber is 8.875 inches.

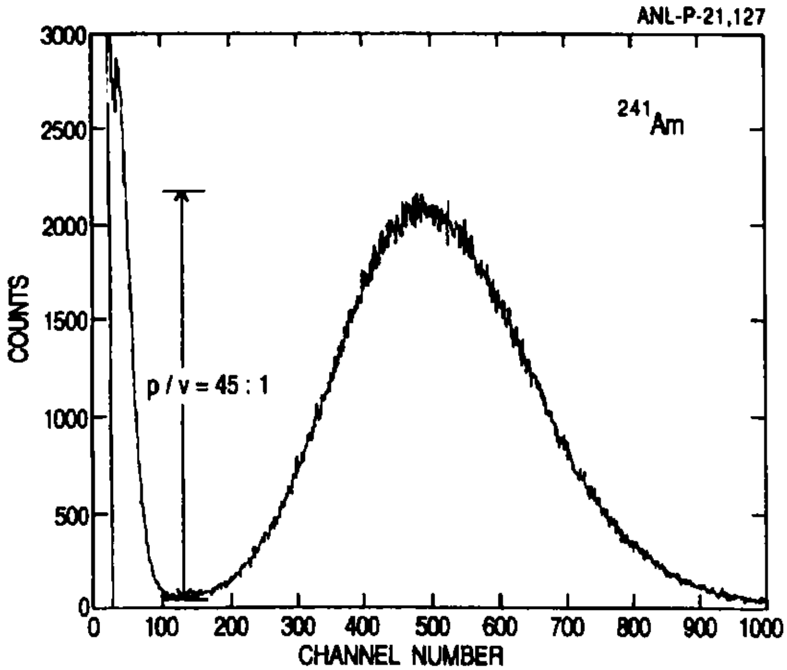

Fig. I-27. Spectrum obtained with one segment of a BGO shield for 59.5-keV γ rays from a ^{241}Am source. Lower energy γ rays and X rays were absorbed by a 0.25-mm-thick copper foil and the aluminum cladding of the BGO scintillator.

The second chamber will be used in conjunction with the final support frame for GAMMASPHERE. While the designing of the chamber is only in its initial phase, it was decided that it will also consist of two spun Al hemispheres. The chamber will have a diameter of 14 inches thus taking up most of the space available between the target and heavimet shielding. A target ladder will also be designed for use with the chamber.

c.3 <u>Mechanical Dimensions of BGO Detectors</u> (T. L. Khoo, M. P. Carpenter, I. Ahmad, R. V. F. Janssens, T. Lauritsen, K. Wood,* T. Barz,* and V. Kubelius†)

The mechanical specifications for the BGO detectors are extremely demanding. A large tapered irregular hexagon has to be mounted within a +0/-0.010" zone of tolerance of its true profile to ensure accurate geodesic packing. This requires not only that its 0.020" thin can mechanically conforms, but that the can be attached to the backplate (from which the detector is supported) within an accuracy of <0.03°. To check dimensions to such accuracy requires use of a so-called coordinate measuring machine. The measurements are performed at Argonne in the Inspections Department of Central Shops and also by independent companies for the detector manufacturers. Fabrication of the detector to these exact demands has proven to be a challenge. Only one of the first 14 detectors from two separate manufacturers has met the mechanical specifications completely. However, they are very close to fully conforming and deviate outside the zone of tolerance by a maximum of 0.008" on one or two sides.

We invested extensive effort in working with the manufacturers in order to obtain detectors which meet the specifications and to develop methods for ensuring that future detectors fully conform. For one manufacturer we provided aluminum plugs for forming the cans, as well as molds for both assembling and checking the detectors. It is expected that newly implemented improvements in manufacturing procedures will produce detectors that meet our demanding specifications.

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*Inspections Department, Central Shops, Support Services Division, ANL,
†Engineering Physics Division, ANL

c.4 GAMMASPHERE Software Development (T. Lauritsen, I. Ahmad, M. C. Carpenter, R. V. F. Janssens, and T. L. Khoo)

ANL participated in the proposal phase for the national GAMMASPHERE project and has agreed to take the responsibility to develop elements of the software for the project.

An event simulator for the electronics and GAMMASPHERE software was written and is currently in use. We developed software to gain match the 110 Ge detectors and, furthermore, will develop algorithms for online corrections of gain drifts. Algorithms were developed to use the Compton-scattered gamma rays from the Ge detectors into the BGO detectors for the gain matching of the latter. The 770 BGO detectors, used for the Compton suppression of the Ge detectors, are shielded by heavymet from gamma rays emitted from the target position. The technique involves 2D analysis of coincidence data and will be much faster than a more cumbersome method where sources have to be placed behind the individual BGO detectors.

We will develop algorithms to set the thresholds in the front-end VXI boards both for the Ge and BGO detectors and we will develop procedures to use time structure information collected along with the energy signal to correct for the deficits in the energy collection in the Ge detectors. In addition, events with incomplete charge collection due to neutron damage will be identified.

ANL will write software to align and monitor the time peaks both for the Ge and BGO detectors, as well as software to monitor the peak-to-total ratios of the Compton-suppressed spectrometers. We shall also explore using 2D time gates to suppress false Compton rejection due to neutron events in the BGO detectors and to discriminate against neutron-induced events in the Ge detectors. Finally, we will be involved in the development of the user interface for the control and monitoring of the GAMMASPHERE array.

d. Status of the Argonne Notre Dame BGO Gamma-ray Facility at ATLAS (R. V. F. Janssens, M. P. Carpenter, J. Falout, J. Goral, J. Joswick, T. L. Khoo, T. Lauritsen, J. Timm, P. Wilt, Y. Liang, and I. G. Bearden*)

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 continued on several fronts.

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* Resident Graduate Student from Purdue University

-- Because of neutron damage, annealing was performed on seven detectors. Two of these were annealed twice. The performance of the detectors was recovered in every case.

-- Maintenance and repairs had to be performed on several electronics modules and, in particular, on some of the CAMAC units. None of these problems affected an experiment for more than a couple of hours.

-- Preventive maintenance was performed on the LN_2 filling system (inspection of all filling lines and check of the various functions of the control modules).

-- Software programs for automatic gain matching and other control parameters of the array elements and CSGs were upgraded.

-- The first installation of 10 of the CSGs at the FMA took place last summer and the following activities connected to this move took place:

(1) the support which allows the placement of 10 detectors around the target location was installed and aligned.

(2) a small target chamber suitable for use with the CSGs was built and installed. Special attention was devoted to the specific requirements of minimal mass from which γ rays can scatter, the availability of a mount for a monitor Si detector inside the vacuum, the availability of a target ladder with a minimum of three target positions, the possibility to use a reset foil to equilibrate the charge-state distribution of nuclei recoiling in the FMA, and the possibility to move the FMA to small angles away from 0°.

(3) the LN_2 filling system was duplicated and installed.

(4) most of the electronics modules for handling the energy and time information as well as for performing the logic decisions were purchased and installed.

(5) the move of the 10 CSGs from the so-called BGO area to the location in front of the FMA was performed in less than a day and did not require the Ge detectors to be warmed up.

It is anticipated that moves between the two target locations will be performed on a routine basis, depending on the needs of the experimental program.

e. <u>The Argonne Silicon Strip Detector Array</u> (A. H. Wuosmaa, R. R. Betts, M. Freer, 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

[1] A. H. Wuosmaa, B. B. Back, I. G. Bearden, R. R. Betts, M. Freer, J. Gehring, B. G. Glagola, Th. Happ, D. Henderson, and P. Wilt, Proc. of Int. Conf. on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-ray Detector Arrays, 418 (1992).

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[1] consists of four double-sided silicon strip detectors (DSSDs), each 5×5 cm^2 in area, with front and back sides divided into 16 strips. The detectors are thus effectively segmented into 256 pixel regions within the 5×5 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 were 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 were 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 their 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 angular 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. Also, we plan to improve the design of the custom-built multi-channel preamplifiers, in order to better their reliability and performance.

A further addition to the present array design which was implemented is the addition of detector elements for fast vetoing of events in which high-energy light particles penetrate the DSSD. The veto detectors consist of 5 × 5 cm^2, 300-μm thick silicon wafers divided into quadrants, positioned behind the four DSSDs. In a recent experiment these quadrant detectors were used to veto high- energy alpha particles which penetrate the front DSSD element, and very effectively suppress the data rate arising from these uninteresting events. This assembly could also easily serve as a highly-segmented, X-Y position-sensitive E-ΔE 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.

f.1 Calculations of the Response of the Focal-Plane Detector at the Split-pole Spectrograph (J. W. Katz* and K. E. Rehm)

In order to optimize the Z-identification of the Bragg-curve detector for reactions with medium-mass projectiles, a computer program was developed which simulates the response of the focal-plane detector at the split-pole spectrograph. Using the energy-loss tables of Ziegler, the program calculates the range of the incident particles in the Bragg-curve detector taking into account the energy losses in the gas of the parallel-plate avalanche detector and in the various pressure and electrode foils. The calculations were compared with experimental results for ions up to Z = 32 and good agreement was observed. An important factor limiting the Z-resolution is the angle magnification of the split-pole spectrograph which, at an incident angle in the focal plane of 45°, leads to large variations in the range of the incident ions. The new program also allows the prediction of the optimum pressure in the Bragg-curve detector and to select the correct entrance aperture to achieve the best Z-resolution.

*Summer Student Research Participant, North Texas State University

f.2 The Study of Fusion Reactions with a Gas-Filled Magnetic Spectrograph (K. E. Rehm, J. Gehring,* D. Henderson, W. Kutschera, and M. Paul†)

We started a program to measure excitation functions of fusion yields using a gas-filled spectrograph. Normal ΔE-E techniques are limited by the count rate the detectors can handle. We 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 a 1 μ thin Mylar entrance foil, 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 efficiency of the detector system for fusion cross

*Resident Graduate Student from The University of Chicago, †Hebrew University, Israel section measurements was determined by detecting evaporation residues (ER) from the systems $^{32}S + ^{64}Ni$ and $^{58}Ni + ^{64}Ni$. A comparison with cross sections measured previously for these two systems showed good agreement.

In the experiments it was observed that the magnetic rigidity Bρ of the ER's relative to the rigidity of the projectile increases at lower bombarding energies. Simulation calculations of this effect using a modified RAYTRACE code are presently being performed.

g. A Particle Ball for GAMMASPHERE (R. R. Betts, A. H. Wuosmaa, C. J. Lister,* and D. Blumenthal*)

The availability of the 110-element gamma-ray spectrometer, GAMMASPHERE, will open up many exciting new possibilities for charged-particle gamma-ray coincidence measurements and will allow new physics questions to be addressed. Examples include; properties of highly-excited high-spin nuclei, exotic states in light nuclei, detailed study of pair- and multi-pair transfer etc.

We have started the conceptual design and specification of a "particle-ball" for use with GAMMASPHERE - and as a stand-alone instrument. The requirements of coverage, energy and angular resolution and particle identification lead us to consider a 10-cm radius sphere covered with 50 5×5 cm^2 double-sided strip detectors. The major questions which arise from this concept concern the readout of the 2500 energy and timing channels that such a configuration requires. We are currently exploring the current state of IC technology for strip detector readout, to see if this can be adapted for use in the detection of charged particles in the 1-20-MeV range with good energy and time resolution.

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*Yale University

h. Physics Division Computer Facilities (D. R. Cyborski, T. H. Moog, and J. Sasso)

The Physics Division maintains several computer systems for data analysis, general-purpose computing, and word processing. Prior to this year, this work was concentrated primarily on two VMS VAXclusters within the Division. Over the past year, these capabilities have broadened considerably with the addition of several RISC-based UNIX workstations.

The main Divisional VAXcluster consists of two VAX 3300s configured as a dual- host system serving a variety of satellite nodes. This configuration has lead to a significant decrease in our downtime and maintenance costs with a marked improvement in performance. These machines act as boot nodes and disk servers to seven other satellite nodes consisting of two VAXstation 3200s, three VAXstation 3100 machines, a VAX-11/750, and a MicroVAX II. These machines operate as a seamless VAXcluster with users free to choose among the system best configured for their particular application. All of the satellite machines have local disks of about 600 MB for paging, swapping, and user files. There are three 6250/1600 bpi 9-track tape drives and five 8-mm tapes served to the cluster by the various satellites. Also, two of the satellites (the MicroVAX and VAX-11/750) have DAPHNE front-end interfaces for data acquisition.

Total disk storage for this cluster is about 9.1 GB distributed over 16 devices. The memories of five of the VAXstations were upgraded this year so that they all have at least 16 MB. This now permits large programs to be run on all 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 consisting of two VAXstation 4000/mod 90, of one VAXstation 3200, one VAXstation 3100, a MicroVAX II, and a VAX-11/750. The weak-interactions MicroVAX II is equipped with a 9-track tape drive and a DAPHNE data-acquisition system.

The ATLAS and Dynamitron VAX-11/50s continue to operate reliably. The Dynamitron VAX (also a part of the VAXcluster) is used routinely for data acquisition and replay. The ATLAS VAX (not clustered) provides data acquisition for two simultaneous users at the ATLAS accelerator, as well as replay when CPU time and memory are available. A new VAX-4000 has been acquired to serve as a dedicated acquisition computer for the APEX experiment.

In addition to these VMS capabilities there has also been a significant migration towards Unix with the installation of networks of IBM, Sun, and Silicon Graphics RISC-based workstations. The Theory Group has installed an IBM RS/6000 workstation and several X-windows terminals. The Argonne members of Fermilab experiment E665 have installed two Silicon Graphics Indigo workstations which are being used for high-level data analysis. The Division has also acquired two Sun IPC and one IPX SPARCstations. These are being used for data analysis, simulations, and CAD/CAM. It is intended to use these machines for the development of a new Unix-based data-acquisition system to eventually replace DAPHNE.

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

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 recently experienced some difficulty in 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 uses DAPHNE software in combination with the MSU/NSCL front end for on-line data analysis. During the past year, two additional MSU/NSCL front ends have been acquired to both serve as backups for the APEX hardware and to allow other complex experiments to use this more intelligent front end.

In addition to this new DAPHNE/MSU acquisition option, we have also developed a relatively inexpensive front-end interface for simple, low-rate applications such as setup and detector tests. This so-called Budget Acquisition DAPHNE (BAD) system consists of a Hytec 1340 list processor and a Hytec 1365 Ethernet crate controller in a single CAMAC crate. This system interfaces to our building-wide Ethernet ThinNet and may thus be used remotely throughout the building. The first such system now sees regular use in the testing of detectors for the GAMMASPHERE project and we plan to procure additional BAD systems. We plan to begin to develop sorting capabilities on our Unix machines so that data from either the MSU/NSCL front ends or BAD systems can be processed with the faster, cheaper, dedicated RISC processors.

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

The Physics Division operates a target development laboratory that produces the thin foil targets needed for experiments performed at the ATLAS and Dynamitron accelerators. Targets are not only produced for the Physics Division but also for other divisions 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 by evaporation included Au, ^{10}B, B_2O_3, Be, ^{12}C, ^{40}Ca, ^{59}Co, ^{170}Er, La, ^{24}Mg, $^{92,100}Mo$, ^{150}Nd, $^{58,64}Ni$, ^{208}Pb, PbS, ^{28}Si, ^{122}Sn, Ta, UF_4, Valine, $^{182}WO_3$ and ^{94}Zr. Stretched targets of Al, Au, and Ni along with metalized mylar were produced for an atomic physics experiment at MSU. A number of large-area aluminized polypropylene foils were needed for preliminary secondary beam studies at ATLAS.

Using our small rolling mill, targets of Al, Cd, Cu, Fe, $^{155,156}Gd$, Mg, $^{58,60,64}Ni$, ^{208}Pb, ^{108}Pd, Ti, and Zn have been produced.

Carbon stripper foils of 2 $\mu g/cm^2$ for use in the tandem as well as other thicknesses for additional stripping are now being produced routinely by the target laboratory. In addition, numerous carbon foils were prepared for various experimental requirements ranging from 0.6 $\mu g/cm^2$ to 1200 $\mu g/cm^2$. About 1000 carbon stripper foils were prepared in calendar year 1992.

The established inventories of standard ATLAS gold and carbon target foils representing a variety of the most common thicknesses has proved an efficient method for handling urgent requests as well as a readily available supply of backing foils.

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.

Auxiliary equipment used for target development includes a glow-discharge apparatus for plasma deposition, 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.
An upgrade to the inert atmosphere glove box was completed and included the addition of an oxygen analyzer. Also, a multiple cylinder station for handling dry nitrogen was set-up on the service floor. This system has been used successfully for production of self-supporting calcium targets. Future plans call for the addition of a transfer chamber port for transport of sensitive targets to the storage chambers.

The IBM PC-XT laboratory computer is extensively used 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 laboratory. The system allows for acquisition and analysis of alpha-particle film-thickness measurements. Some new applications include data compilation and analysis routines. Also, mechanical drawings needed for shopwork are now drawn using the computer.

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 chamber is now in routine use for target storage. There also exists a bank of vacuum desiccators connected to a mechanically-pumped manifold for use by individual experimenters.

The low-level radioactive target laboratory dedicated to the production of radioactive target foils has seen increased use over the past year. Targets of ThF_4 on beryllium and carbon backings have been prepared in this lab using the large Cooke evaporator system. By the same method, UF_4 targets were prepared for the APEX experiment at ATLAS.

A second, much smaller evaporator system was constructed for close-proximity evaporations of higher-activity materials and is used heavily for radioactive source development. With this evaporator, ^{35}S, ^{14}C, and ^{63}Ni sources were produced for measurements searching for a 17-keV neutrino. Also prepared as internal-conversion sources were ^{57}Co, ^{109}Cd, and ^{139}Ce, all on thin carbon backings.

F. ASSISTANCE TO OUTSIDE USERS OF ATLAS

B. G. Glagola

The continuing strong interest in ATLAS (outside users were involved in 95% of all experiments performed in FY1992) makes it clear that the user-assistance program performs an essential function.

Outside user involvement increased from that in 1991. A user liaison physicist continues to play a key role in channeling assistance to outside users. The major components of his responsibility are: (1) provide the needed information and organizational assistance to committees, workshops, and other meetings involving outside users; (2) provide users with technical information about ATLAS and its experimental systems, and to provide instruction in its use; (3) assist outside users in all aspects of initiating and planning an experiment; (4) to the extent that is appropriate and feasible, assist users in the actual performance of experiments; (5) provide instruction and help with the use of computer hardware and software; (6) instruct the users in the safety procedures to be followed when using the ATLAS facility; (7) assist in coordinating the operation of the technical support group; and (8) provide an interface between the user and the technical support and ATLAS operation groups.

Because of the larger backlog of experiments, only one PAC meeting was held during FY1992. The Program Advisory Committee (PAC) for ATLAS (consisting of five members from other institutions and two from Argonne) meets regularly during the year. A PAC meeting was held on 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 J. Lister (Yale University), Robert McGrath (SUNY at Stony Brook), K. Ernst Rehm (ANL), Udo Schroeder (University of Rochester), and David Ward (Chalk River Nuclear Laboratories). The PAC reviewed 24 proposals for 134 days of running time at the meeting. The demand for running time at ATLAS continues to be more than double the time available on the accelerator.

The ATLAS User Executive Committee organized a User Group meeting during the October 1992 Division of Nuclear Physics APS meeting held in Santa Fe, NM. Nominations were taken for an Executive Committee election. The meeting was attended by approximately 40 scientists. The main topics of discussion were the FMA project, the status of the ATLAS positive-ion injector and APEX, the positron experiment at ATLAS. The new ATLAS Executive Committee consists of Christopher J. Lister (Yale University),as Chairperson, Robert McGrath (SUNY at Stony Brook), Stephen Sanders (University of Kansas), and Frank Wolfs (University of Rochester).

Outside users are heavily involved 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. "Research at ATLAS" on the FMA. An ANL-FSU-MSU-Princeton-Rochester-Washington-Yale collaboration is starting an experimental program to investigate and resolve the question of "anomalous positron peaks" that have been observed at GSI. The members of the outside APEX collaboration are: S. Austin, D. Bazin, E. Kashy, D. Mercer, J. Winfield, J. Yurkon, Michigan State University; J. Greenberg, C. J. Lister, P. Chowdhury, K. Chan, A. Chishti, N. Kaloskamis, Yale University; F. Calaprice, Princeton University; A. Hallin, M. Liu, Queens University; J. Fox, E. Roa, Florida State University; F.L.H. Wolfs, S. Gazes, A. Perera, University of Rochester; T. Trainor, University of Washington; D. Mikolas, Cornell University; J. Last, ILL; and M. Maier, Lawrence Berkeley Laboratory. The installation of the apparatus is being completed. For more details see Section I.E.b. "Research at ATLAS" on the APEX project.

The magnitude of the outside use of ATLAS during the past year has been substantial, as shown by 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.

The Physics Division thanks the University of Chicago Board of Governors for their support of the ATLAS User Program.

a. Experiments Involving Outside Users

All experiments in which outside users participated during FY 1992 are listed below. The spokesperson for each experiment is given in square brackets after the title. The names in parentheses are Argonne collaborators.

(1) Quasielastic Reactions of ^{40}Ca+^{208}Pb [Kolata]
J. Kolata, S. Dixit, K. Lamkin, R. Tighe, M. Belbot, M. Zahar, W. Chung, University of Notre Dame; J. Gehring, University of Chicago; (K.E. Rehm)

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

(3) FMA Commissioning Tests [Davids]
K. Bindra, Vanderbilt University; J. Vega, Univ. Nac. Auto. de Mexico; W. Chung, University of Notre Dame; I. Crawford, Iowa State University; (C. Davids, D. Henderson, W. Kutschera, M. Freer, R.R. Betts, A. Wuosmaa, B. Back, T. Lauritsen)

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

(5) Two Photon Decay of He-like Br^{33+} [Dunford]
A. E. Livingston, University of Notre Dame; L. Curtis, University of Toledo; (R.W. Dunford, S. Cheng, E.P. Kanter, H.G. Berry, C.A. Kurtz, J.A. Suleiman)

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

(7) Angular Distribution Measurement for $^{12}C+^{12}C \rightarrow ^{12}C(0_2^+)+^{12}C(0_2^+)$ Inelastic Scattering [Wuosmaa]
I. Bearden, Purdue University; T. Happ, GSI; J.C. Gehring, University of Chicago; (A.H. Wuosmaa, B.B. Back, R.R. Betts, M. Freer, D.J. Henderson, B.G. Glagola)

(8) Alpha Decay Rates of ^{180,182}Pb [Toth]
K. Toth, Oak Ridge National Laboratory; K. Bindra, Vanderbilt University; J.D. Robertson, University of Kentucky; D.M. Moltz, Lawrence Berkeley Laboratory; W.B. Walters, University of Maryland; W. Chung, University of Notre Dame; C.R. Bingham, University of Tennessee; (C.N. Davids, B.B. Back, D.J. Henderson)

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

(10) The Primary Excitation Mechanism in $^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C$ [Freer]
T. Happ, GSI; J.C. Gehring University of Chicago; (M. Freer, A.H. Wuosmaa, R.R. Betts, B.B. Back, D.J. Henderson,)

(11) APEX Beam Tests [Betts]
T. Happ, GSI; E. Kashy, J. Winfield, J Yurkon, Michigan State University; A. Perrera, University of Rochester; D. Bazin, GANIL; J. Greenberg, N. Kaloskamis, A. Chishti, C. Lister, Yale University; A. Hallin, M. Liu, Queens University; (R.R. Betts, A.H. Wuosmaa, W. Kutschera, B.B. Back, J.P. Schiffer, M. Freer, I. Ahmad, D.J. Henderson, R.W. Dunford, S. Freedman)

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

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

(14) Search for "Necked" Superdeformation in the A = 90 Region [Garg]
U. Garg, A. Aprahamian, University of Notre Dame; W. Reviol, University of Tennessee; I. Bearden, Purdue University; F. Soramel, University of Padova; (I. Ahmad, T.L. Khoo, M.P. Carpenter, R.V.F. Janssens, T. Lauritsen, Y. Liang, R. Henry)

(15) Search for Identical Superdeformed Bands in ^{192}Tl [Carpenter]
F. Soramel, University of Padova; I. Bearden, Purdue University; W. Reviol, J. Lewis, University of Tennessee; S. Pilotte, University of Ottawa; (M.P. Carpenter, T.L. Khoo, R.V.F. Janssens, I. Ahmad, T. Lauritsen, Y. Liang, R. Henry)

(16) FMA Studies of p-Rich Nuclei with $Z > 64$, $N < 82$ [Daly]
P. Daly, Z. Grabowski, D. Nisius, B. Fornal, R. Mayer, I. Bearden, Purdue University; W. Chung, University of Notre Dame; K. Bindra, Vanderbilt University; (T.L. Khoo, R.V.F. Janssens, M.P. Carpenter, T. Lauritsen., I. Ahmad, C.N. Davids, R. Henry, Y. Liang)

(17) Feeding Into and Decay Out of the Superdeformed Band in ^{192}Hg [Lauritsen]
I. Bearden, B. Fornal, Purdue University; U. Garg, University of Notre Dame; F. Soramel, University of Padova; W. Reviol, University of Tennessee; (Y. Liang, T. Lauritsen, T.L. Khoo, I. Ahmad, M.P. Carpenter, R.V.F. Janssens)

(18) Test of FMA Moving Tape Collector [Davids]
F. Soramel, University of Padova; K. Bindra, Vanderbilt University; W. Chung, University of Notre Dame; W.B. Walters, University of Maryland; E. Zganjar, Louisiana State University; J. Hill, Iowa State University; (C.N. Davids, D.J. Henderson, E. Badi)

(19) $\gamma\gamma$ Coincidence Studies of Few Nucleon Transfer in ^{122,124}Sn + ^{80}Se Reactions [Daly]
B. Fornal, R. Mayer, R. Broda, Z. Grabowski, P. Daly, I. Bearden, Purdue University; F. Soramel, University of Padova; (T. Lauritsen, M.P. Carpenter, R.V.F. Janssens, R. Henry, T.L. Khoo, Y. Liang)

(20) FMA Optics Test [Davids]
K. Bindra, A. Ramayya, W.-C. Ma, Vanderbilt University; W. Chung, University of Notre Dame; F. Soramel, University of Padova; I. Bearden, Purdue University; (C.N. Davids, B.B. Back, D.J. Henderson, R.V.F. Janssens, M.P. Carpenter, T. Lauritsen, Y. Liang)

(21) AMS of ^{59}Ni and Its Occurrence in Extraterrestrial Matter [Kutschera]
D. Berkovitz, M. Paul, Hebrew University; (B.G. Glagola, I. Ahmad, R.C. Pardo, K.E. Rehm, W. Kutschera)

(22) Lifetime Measurements for Intercombination Transitions in Kr^{22+} - Kr^{24+} [Träbert]
E. Träbert, Ruhr-Universität Bochum; A. E. Livingston, University of Notre Dame; L. Curtis, University of Toledo; (R.W. Dunford, H.G. Berry, S. Cheng, C.A. Kurtz, J.A. Suleiman)

(23) Superdeformation in ^{192}Tl [Moore/Janssens]
F. Soramel, University of Padova; I. Bearden, Purdue University; U. Garg, University of Notre Dame; W. Reviol, University of Tennessee; (Y. Liang, M.P. Carpenter, R. Henry, T.L. Khoo, T. Lauritsen, R.V.F. Janssens)

(24) Superdeformation in ^{196}Pb [Moore/Liang]
F. Soramel, University of Padova; W. Reviol, University of Tennessee; U. Garg, University of Notre Dame; (Y. Liang, M.P. Carpenter, I. Ahmad, R. Henry, T.L. Khoo T. Lauritsen, R.V.F. Janssens)

(25) Violation of K-Selection Rules in ^{176}W High-K Isomers [Chowdhury]
P. Chowdhury, B. Crowell, C. Lister, S. Freeman, Yale University; F. Soramel, University of Padova (Y. Liang, R. Henry, T. Lauritsen, T.L. Khoo, R.V.F. Janssens)

(26) Heavy Residues in ^{27}Al + ^{181}Ta [Freeman]
S. Freeman, C. Lister, P. Chowdhury, B. Crowell, Yale University; W. Chung, University of Notre Dame; K. Bindra, Vanderbilt University; F. Soramel, University of Padova; (C.N. Davids, R.V.F. Janssens, D.J. Henderson, T. Lauritsen, M.P. Carpenter, Y. Liang, B.B. Back)

(27) Test of Bragg Curve Counter on FMA [Kolata]
J.J. Kolata, R. Thompson, W. Chung, University of Notre Dame; (C.N. Davids, D.J. Henderson)

(28) n-n and n-d Correlations Test [DeYoung]
P. DeYoung, D. Peterson, S. DeCair, T. Butler, N. Shaw, C. Dykstra, Hope College; G. Gilfoyle, University of Richmond; R. Kryger, Michigan State University; J. Hinnefeld, Indiana University at South Bend; J.J. Kolata, M. Belbot, University of Notre Dame; M. Kaplan, Carnegie-Mellon University

(29) Beam Tests of Hybrid MWPC/Bragg-Curve Detector [Sanders]
S. Sanders, F. Prosser, K. Farrar, A. Hasan, D. Desbien, University of Kansas; (D.J. Henderson)

(30) Comparison of Beam Rejection Capability for 0° Operation between the Argonne FMA and the Legnaro Recoil Mass Spectrometer CAMEL [Signorini]
F. Soramel, C. Signorini, F. Scarlassara, P. Spolaore, University of Padova; K. Bindra, Vanderbilt University; W. Chung, University of Notre Dame; (C.N. Davids, D.J. Henderson)

(31) Test of Rotating Target for Secondary Beam Development [Kutschera]
D. Berkovits, Hebrew University; (W. Kutschera, R.C. Pardo, K.E. Rehm, J.P. Schiffer)

(32) Study of the $^{12}C + ^{12}C \rightarrow 3(^{8}Be)$ Reaction [Wuosmaa]
I. Bearden, Purdue University; (A.H. Wuosmaa, B.B. Back, R.R. Betts, B.G. Glagola, M. Freer, D.J. Henderson)

(33) Fusion with the Gas-Filled Magnet [Rehm]
F. Soramel, University of Padova; J. Gehring, University of Chicago; (K.E. Rehm, W. Kutschera, B.G. Glagola, A.H. Wuosmaa, D.J. Henderson)

(34) Measurement of the Superdeformed Ridge Structure in ^{192}Hg [Carpenter]
F. Soramel, University of Padova; W. Chung, University of Notre Dame; K. Bindra, Vanderbilt University; W. Reviol, University of Tennessee; M. Drigert, Idaho National Engineering Laboratory; I. Bearden, R. Mayer, D. Nisius, B. Fornal, Purdue University; (M.P. Carpenter, R. Henry, R.V.F. Janssens, T.L. Khoo, Y. Liang, T. Lauritsen, C.N. Davids)

(35) High-Temperature Phenomena in Proton-Rich Nuclei [McGrath]
R. McGrath, A. Caraley, K. Brinkmann, N. Gan, B. Fineman, State University of New York at Stony Brook; P. DeYoung, Hope College; G. Gilfoyle, University of Richmond; (B.G. Glagola)

(36) Magnetic Moments of Mirror Nuclei [Koller]
N. Koller, T. Vass, A. Mountford, Rutgers University; G. Goldring, Weizmann Institute; I. Bearden, Purdue University; (C.N. Davids, R. Henry, T. Lauritsen, R.V.F. Janssens, Y. Liang, M.P. Carpenter)

(37) Charge State Dependence of Lifetimes and Fluorescent Yields in ^{83}Kr [Phillips]
W. Phillips, J. Copnell, University of Manchester; M. Paul, Hebrew University; (K.E. Rehm, B.G. Glagola, I. Ahmad, J.C. Gehring, W. Kutschera)

b. Outside Users of ATLAS and of ATLAS Technology During FY 1992

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

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

(2) University of Notre Dame
- A. Aprahamian
- * M. Belbot
- * W. Chung
- * S. Dixit
- U. Garg
- J. Kolata
- * K. Lamkin
- A. E. Livingston
- * S. Naguleswaran
- * R. Thompson
- * R. Tighe
- * J. Walpe
- M. Zahar

(3) Purdue University
- * I. Bearden
- R. Broda
- P. Daly
- B. Fornal
- Z. Grabowski
- * R. Mayer
- * D. Nisius
- * L. Richter
- M. Sferrezza

(4) Idaho National Engineering Lab
- M. Drigert

(5) Vanderbilt University
- * K. Bindra
- J. Kormicki
- W.-C. Ma
- A. Ramayya

(6) University of Pennsylvania
- * S. Barrow
- J. Murgatroyd
- * K. Pohl
- N. Wimer
- R. Zurmühle

(7) SUNY Stony Brook
- K. Brinkmann
- * A. Caraley
- * B. Fineman
- * N. Gan
- R. McGrath

(8) Lawrence Livermore National Lab
- T.-F. Wang

(9) University of Rochester
- F. Wolfs
- S. Gazes
- * A. Perera
- C.-H. Yu

(10) Carnegie-Mellon University
- M. Kaplan

(11) University of Chicago
- * J. Gehring

(12) Technical University of Munich
- B. Schneck

(13) University of Toledo
- L. Curtis

(14) NSC, New Delhi
- N. Anantaraman
- G. Mehta
- P. Potukuchi
- A. Roy

(15) Hope College
- * T. Butler
- P. DeYoung
- * S. DeCair
- * C. Dykstra
- * D. Peterson
- * N. Shaw

(16) Louisiana State University
E. Zganjar

(17) University of Padova
F. Soramel
F. Scarlassara
C. Signorini
P. Spolaore

(18) University of Maryland
W. Walters
L. Conticcio

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

(20) Rutgers University
N. Koller
A. Mountford
T. Vass

(21) Ruhr Universität Bochum
E. Träbert

(22) Hebrew University
M. Paul
D. Berkovitz

(23) University of Tennessee
C. Bingham
* J. Lewis
L. Riedinger
W. Reviol

(24) Florida State University
J. Fox
* E. Roa

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

(26) Michigan State University
S. Austin
D. Bazin
E. Kashy
R. Kryger
D. Mercer
J. Winfield
J. Yurkon

(27) Princeton University
F. Calaprice

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

(29) Oak Ridge National Laboratory
K. K. Toth

(30) Tennessee Technological Univ.
R. Kozub

(31) University of Richmond
G. Gilfoyle

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

(33) Indiana State Univ. at South Bend
J. Hinnefeld

(34) University of Manchester
J. Copnell
W. Phillips

(35) University of Washington
T. Trainor

(36) GSI, Darmstadt
T. Happ

(37) University of Kentucky
J. Robertson

(38) Iowa State University
I. Crawford
J. Hill
F. Wohn

(39) University of Ottawa
S. Pilotte

(40) Queens University, Ontario
A. Hallin
M. Liu

(41) Cornell University
D. Mikolas

(42) Weizmann Institute
G. Goldring

c. Summaries of the Continuing User Programs for FY 1992

c.a. The University of Notre Dame

c.a.1. Nuclear Physics (U. Garg, S. Dixit, J. J. Kolata, W. Reviol (University of Tennessee), A. Aprahamian, B. Davis, S. Naguleswaran, J. Walpe)

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 many experiments performed with the BGO gamma-ray facility completed recently. 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. In addition 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.

c.a.2. Atomic Physics (A. E. Livingston)

In a collaboration with the Atomic Physics group at 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 2^3S_1-2^3P_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 collaboration between Argonne and E. Träbert of Ruhr Universität at Bochum measured the lifetimes of intercombination transitions in Mg-like, Al-like and Si-like krypton. The group is also participating in measurements of the forbidden transitions in helium-like ions. The excited state is formed in a thin-carbon foil which can be moved relative to the Si(Li) 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 data analysis was completed for a measurement of the lifetime of the 2^1S_0 level in helium-like bromine. A measurement of the lifetime of the 2^3P_2 level in helium-like krypton is planned for this year.

c.b. Purdue University (P. Daly, Z. Grabowski, R. H. Mayer, D. Nisius, B. Fornal, I. Bearden)

The Purdue University group, including several thesis students, is working on a measurement of high-spin nuclear states at ATLAS. They use in-beam gamma-ray techniques to investigate several aspects of nuclear structure at high spin, testing the validity of shell-model calculations for high-spin-yrast states near Z = 50. The nuclei are produced via deep inelastic reactions, rather than with the more conventional fusion reactions. This technique allows the study of neutron-rich nuclei that cannot be studied by other means. The group will also be studying proton-rich nuclei with N~82 using the FMA and an electron spectrometer. Furthermore, I. G. Bearden is a Ph.D. student, resident at ANL, performing his thesis work under the supervision of R. V. F. Janssens.

c.c. University of Kansas (S. Sanders, F. W. Prosser, K. Farrar, A. Hasan, and D. Desbien)

The group continued to study the process where relatively light compound nuclei ($A_{cn} < 60$) 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. At the end of the year this group had a successful run, in collaboration with researchers from Sao Paulo, Brazil; Strasbourg, France; and Argonne, in which they studied the fission of ^{48}Cr as populated in the ^{36}Ar + ^{12}C reaction. Last year this group studied ^{48}Cr fission using the ^{24}Mg + ^{24}Mg reaction. In the recent run, gamma rays emitted from the fission fragments were detected using the Argonne-Notre Dame gamma-ray facility. The fragments were detected in two large-area, multi-wire proportional counters with mass and energy determination achieved using the kinematic coincidence technique. In addition to this particle-particle gamma coincidence measurement, where very good Q-value resolution is possible using the kinematic coincidence technique, the Kansas Bragg-curve detector was also employed to obtain high-statistics particle-gamma coincidence data. The results from this measurement will allow a comparison to be made of the fission behavior of ^{48}Cr as populated through reactions of very different entrance-channel mass asymmetry.

c.d. 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 calculations. 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 Ca^{19+} was accelerated to 205 MeV and then decelerated to 105 MeV and delivered to the atomic-physics beam line. A crystal spectrometer and a gas target installed on the beam line 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.e. Idaho National Engineering Laboratory (M. W. Drigert)

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

c.f Vanderbilt University (A. V. Ramayya, J. H. Hamilton, K. Bindra, W.-C. Ma, B. R. S. Babu, L. Chaturvedi, and J. Kormicki)

This group has been actively involved in the development and testing of the FMA. Their recent experimental interest has been in furthering the understanding of the light mercury isotopes. In the past year an experiment was performed to enable identification of in-beam gamma rays from ^{181,183}Hg using 10 Compton-suppressed Ge detectors mounted at the target position of the FMA. The evaporation residues were detected using a PPAC detector in the FMA focal plane. Using fragment-gamma coincidences a number of gamma rays have been assigned to ^{181}Hg and ^{183}Hg.

Fragment-gamma-gamma coincidences that were collected will be analyzed for the construction of the level scheme of ^{183}Hg. One member of the collaboration, K. Bindra, who is a Ph.D. student, is at ANL full time under the direction of Cary Davids.

d. ATLAS - Technology Transfer

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

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

Argonne has fabricated the niobium resonators and some auxiliary devices required for the superconducting-linac energy booster being built at Florida State University. Under this arrangement, personnel from FSU have come to ANL to assemble and test the resonators. The main resonator fabrication work for FSU was completed during 1986, but we continue to interact with personnel concerning ongoing refinements in the technology. Topics in which we were most recently involved are (1) a change in the method of cooling the FSU resonators and (2) the transfer of information about fast tuner upgrades. During the past year there was very little interaction.

d.b. 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 accel/decel 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 returned occasionally to assemble and test the resonators. There is a continuing interchange of technical information between ANL and KSU.

d.c. University of Sao Paulo (J. C. Acquadro, N. Added, M. Ferraretto, J. Ordonez, O. Sala, and A. Szanto de Toledo)

Argonne has agreed to assist the University of Sao Paulo (USP) in the construction of a small superconducting heavy-ion linac to serve as an energy booster for projectiles from their 8-MV tandem. This booster will be similar in many respects to the ANL booster linac built in the late 1970s. The ANL contribution to this project will be (1) to build (at USP expense) 14 split-ring niobium resonators and some of the associated rf electronics, (2) to provide technical information, and (3) to train USP staff members in several phases of superconducting-linac technology. Two Brazilian engineers worked at Argonne for one year, gaining experience in cryogenics and in superconducting-resonator technology. Another engineer worked on the new control system at ATLAS for two years, the first year supported by Sao Paulo and the second with direct ANL support. Sao Paulo personnel will return to ANL in 1993 for assembly and testing of the completed resonators. The fabrication of the resonators will be completed in late 1993.

d.d. Nuclear Science Centre, New Delhi (G. Mehta, P. Potukuchi, A. Roy)

Argonne is collaborating with the Nuclear Science Centre (NSC), New Delhi, to develop a new type of superconducting accelerating structure for low-velocity heavy ions. A copper model has been evaluated and the niobium prototype is currently under construction. Some technical details of this project are described in the Superconducting Linac Development section. All funding for the prototype has come from the NSC, and they have also stationed two staff members at ATLAS for the past year to gain experience and work on this project.

II. OPERATION AND DEVELOPMENT OF ATLAS

These sections report on the operation and development of the Argonne Linear Accelerator System (ATLAS) as a National User Facility, for basic research in nuclear physics with high-quality heavy-ion beams. The facility is also used for atomic physics and occasionally for other areas of research, such as materials science. Over half of the beam time is allocated to outside users. A positive-ion injector (PII) was completed and commissioned in FY 1992, significantly upgrading the capabilities of ATLAS, and thereby also creating additional demands for beam time. Including the new PII linac, the complete ATLAS accelerator now consists of 60 independently-controlled superconducting accelerating structures. Beams with masses up to uranium are now available for research. Currently, the facility is on a five-day week operating schedule, but additional funds are being requested beginning in FY 1994 to support expanded operations, about 4500 hours of beam on target for research in FY 1994. The plan is for continued operation at over 5000 hours per year of beam on target for research in successive years. The table below summarizes the statistics of recent ATLAS operations and gives predictions for the near future.

These activities are elaborated on in the sections below. There are progress reports on recent beam developments, as well as on other technical developments at ATLAS, and descriptions of superconducting RF and other accelerator physics R&D projects.

STATISTICS ON ATLAS USAGE

	FY 1992 actual	FY 1993 extrapolated	FY 1994 predicted	FY 1995 predicted
Beam Use for Research (hr)				
Nuclear Physics	3078	3150	4050	4550
Atomic Physics	103	250	350	350
Other	0	100	100	100
Total	3181	3500	4500	5000
Number of Nuclear Experiments Receiving Beam	45	45	50	60
Number of Scientists Participating in Research	123	140	150	150
Institutions Represented				
Universities (U.S.A.)	25	28	29	29
DOE Nat'l Laboratories (incl. ANL)	5	5	5	5
Other	12	12	12	12
Usage of Beam Time (%)				
In-House Staff	30	43	42	42
Universities (U.S.A.)	56	52	53	53
Other DOE National Laboratories	4	2	2	2
Other Institutions	10	3	3	3
Total	100	100	100	100

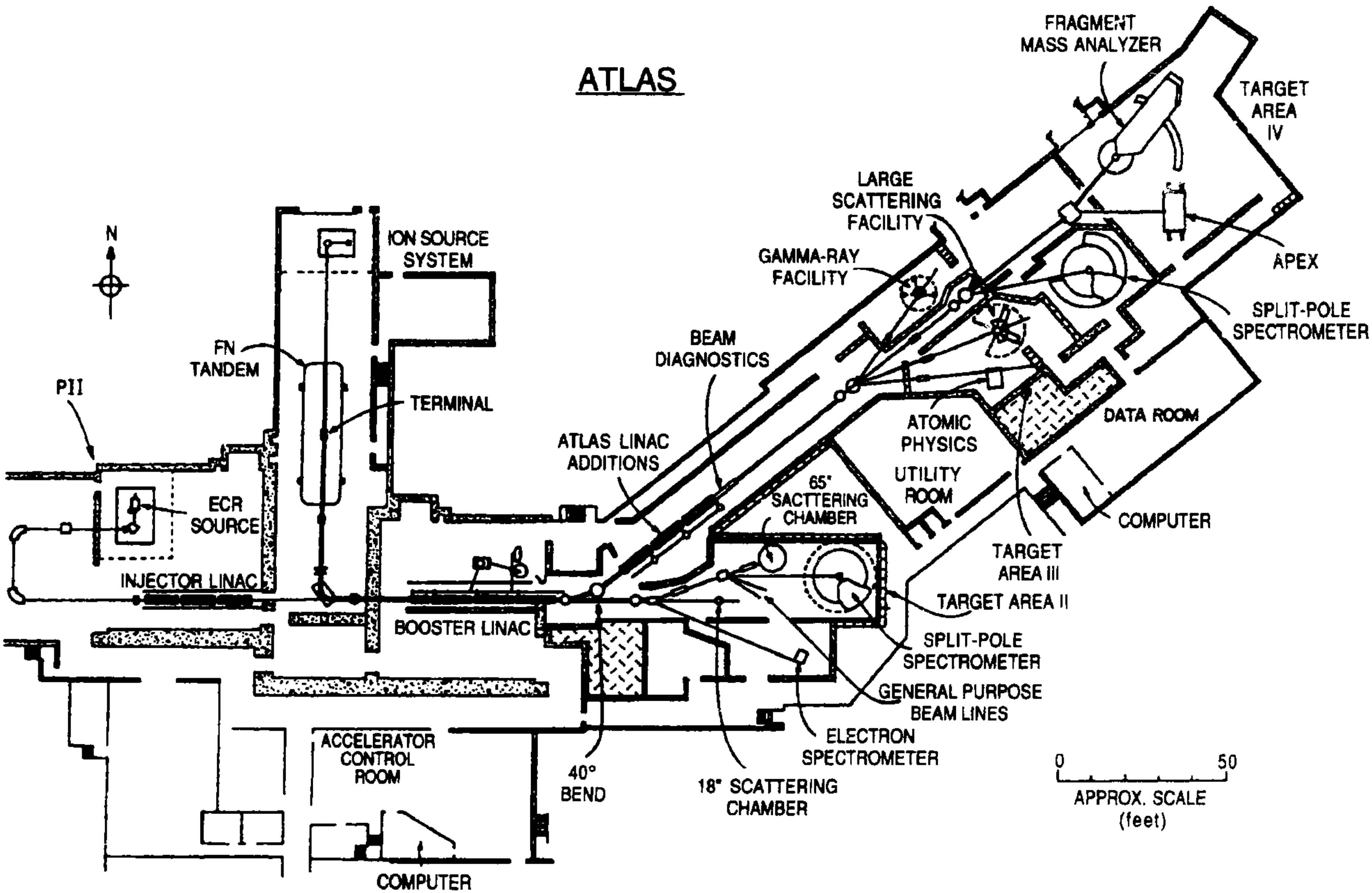

Fig. II-1. Layout of the ATLAS facility showing the new positive-ion injector (PII) on the left, and the newest experimental apparatus, the FMA and APEX, in Area IV on the right.

A. OPERATION OF THE ACCELERATOR

R. C. Pardo, B. Batzka,, P. J. Billquist, J. Bogaty, B. E. Clifft, S. L. Craig, R. E. Harden, D. Herbst, B. Millar, F. H. Munson, Jr., K. Nakagawa, D. R. Phillips, J. R. Specht, P. Strickhorn, B. Tieman, I. R. Tilbrook, R. Vondrasek, and G. Wiemerslage, and G. P. Zinkann

ATLAS experienced a very successful year of operation in FY 1992. Highlights of the year included approval of the ATLAS-PII Safety Analysis Report and the successful completion of the Operational Readiness Review resulting in ATLAS being given "Operational Status" for the complete upgraded system on August 27, 1992. Even before receiving operation status, the new Positive Ion Injector (PII) was used in a "commissioning mode" which allowed beam delivery for certain selected experiments in order to debug the new facility and gain operating experience. The floor plan of ATLAS in Fig. II-1 shows the relationship between the new PII injector and the existing tandem injector and original ATLAS linac.

The "operational" status of ATLAS not only authorizes the use of the PII for the regular experimental program at ATLAS but also enabled the use of the redesigned ATLAS Radiation Interlock System (ARIS). The new system incorporates an elaborate radiation monitoring system with sufficient levels of safety to allow access to experimental areas, and some accelerator areas, while beam is being delivered to target. This important capability has made possible a number of PAC approved experiments which require access to electronics in order to obtain data of sufficient quality. The system has performed continuously since July 1992 with very few problems.

The first acceleration of beam from the new PII occurred on March 30, 1992 when a beam of ^{40}Ar was delivered to the BGO gamma-ray facility for an experiment. Since that time a wide variety of beams have been accelerated for the research program from ^{30}Si through ^{238}U.

Approximately 50% of ATLAS beam time in the second half of 1992 was provided using the new Positive Ion Injector. Such a high demand for beams from the PII has put a premium on bringing the PII into a full production mode of operation. This includes finishing many of the details such as integrating control of the PII into the existing control system, staff training, and hardware improvements. In January 1993 we began to control the PII linac from the main control room for the first time. A new master oscillator system which will allow independent phasing of the major linac sections - PII, Booster, and ATLAS - should allow much improved use of 'old tunes' and improved operating efficiency. Installation of this new system is expected in the summer of 1993.

The most important capability which the new Positive Ion Injector provides the ATLAS facility is the availability of heavy ($A < 100$) beams for the user program. Developing those beams fully is our top priority for the near term and the uranium beam for the APEX experiment is the focus of those efforts.

The first acceleration of uranium with the new Positive-Ion Injector of ATLAS was successfully accomplished during the week of July 27, 1992. A beam of approximately 300 electrical nanoamps $^{238}U^{28+}$ was provided by the ECR ion source and accelerated by the PII linac to 293 MeV. This beam was stripped to a 42+ charge state and further accelerated to 1363 MeV (5.7 MeV per nucleon) by the ATLAS linac. Beam current after stripping and acceleration was 6 electrical nanoamps at the exit of the accelerator (for 300 enA injected).

A second uranium run occurred in the first week of September with similar results in beam energy. For this test, the ceramic uranium oxide UO_2 was used in the source which then delivered up to 500 electrical nanoamps of 28+. For the runs in February and March 1993, it was possible to use the 25+ charge state due to the progress made on the linac upgrade work which is discussed below. A charge-state distribution of uranium from UO_2, shown in Fig. II-2 shows the significant increase in beam current that was realized in moving from the 28+ charge state to the 25+ charge state.

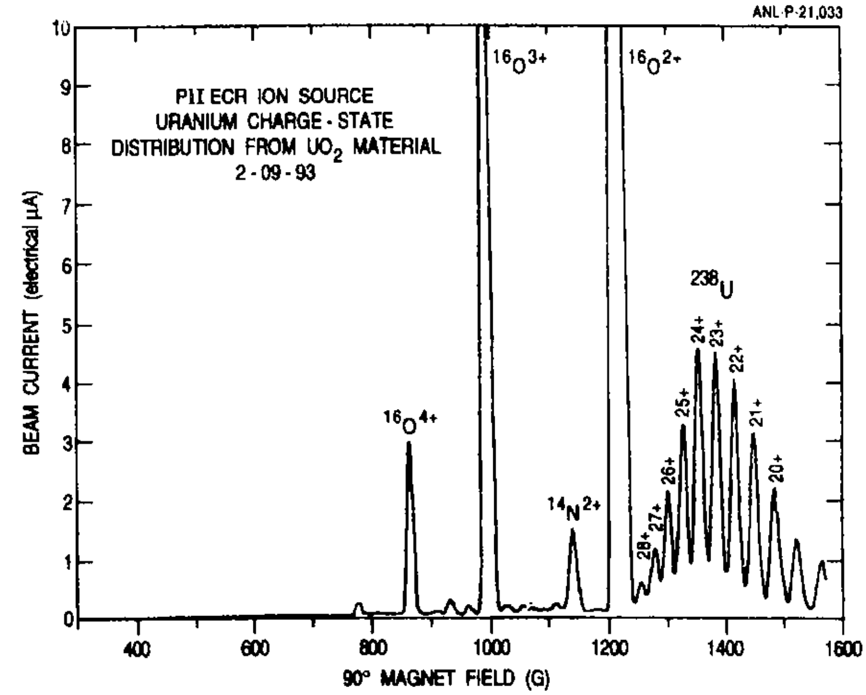

Fig. II-2. Charge states of uranium ions extracted from the ECR ion source at ATLAS.

In February 1993 the results of this effort produced a uranium beam for the APEX experiment with a maximum possible energy of 6.45 MeV/A and delivered 0.5 pna to target at 6 MeV/A. Six weeks later these results were further improved, by changing the accelerated charge states from (27 → 40) to (25 → 40) so that up to 4 pna were delivered to the APEX target at the same energy as the February run. Further improvement in beam current is expected by changing the charge state combination to (25 → 39) in runs later in the Spring 1993.

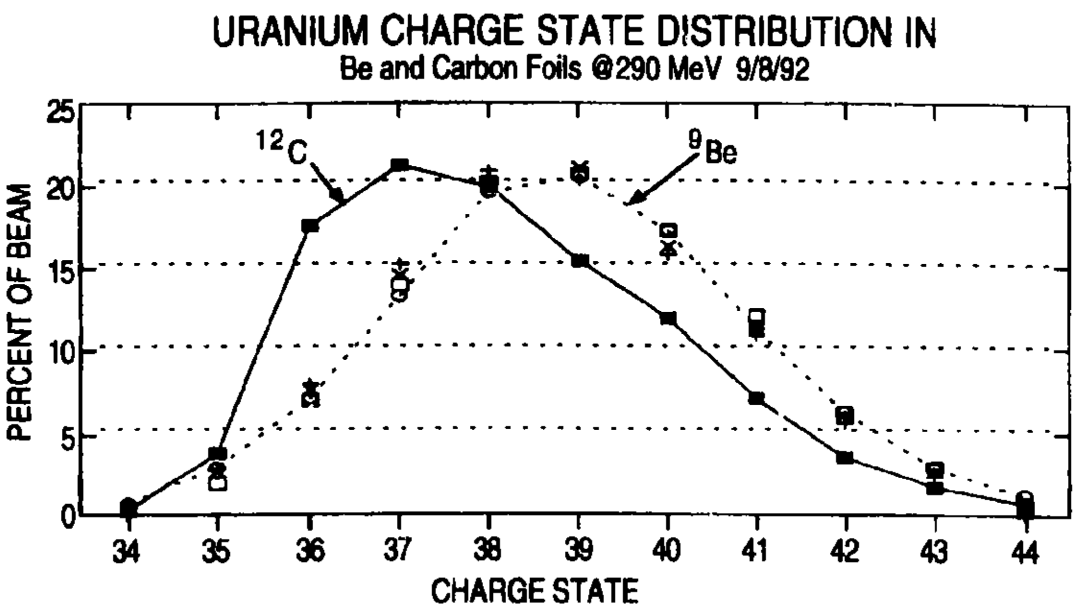

Fig. II-3. Charge-state distributions for uranium beams stripped after PII in carbon and beryllium foils.

For four months following the September uranium trial run, continuous activity was underway on a wide variety of tasks in order to improve the performance of the system for heavy beams. The most important activity was the modification of the velocity profile of the ATLAS linac by replacing five 'V resonators' (ß = 0.155) with 'H resonators' (ß = 0.105) which better match the velocities of beams such as uranium. These upgrade tasks occurred while the facility continued to operate a full research program with lighter mass beams.

The performance of stripper foils is very important to the operation of ATLAS for heavy beams such as uranium. The lifetime of stripping foils for heavy beams is much less than when a foil is used to strip a lighter ion beam. These first runs have generally used 50 microgram/cm^2 ^{12}C foils to strip the uranium beam. Foil lifetimes for these runs have generally been a few hours, and integrated particle fluxes range from 3-6 microamp-hours. This good result for foil lifetimes means that foil usage will not be too serious a problem even for uranium runs.

Self-supporting beryllium foils have also been used as the stripping medium. The use of beryllium foils is appealing because the charge-state distribution from beryllium foils is shifted upward by about 1.5 charge states when compared to carbon foils. Figure II-3 shows a comparison between carbon and beryllium stripping foil charge-state distributions for uranium at 1.2 MeV/A. Beryllium foil lifetime appears to be comparable to the carbon foil lifetimes. These tests of beryllium foils will be continued to see if they are practical for extensive use.

We have begun to expand the operating staff at ATLAS as the first step in going to a seven-day operating schedule. In October 1992 a new operator was added to the staff and began the necessary training process. A second operator was added in January 1993 and began the training process. Extending the scheduled operating week by 1/2 day should be possible in early spring and full seven-day operation is expected to be possible by the fall of 1993. For extended seven-day operation, additional funding to increase the support/maintenance staff at ATLAS must be forthcoming.

B. RECENT IMPROVEMENTS AT ATLAS

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

The development of the new linac control system continues. The backbone of the new system is a commercial software product developed at Los Alamos National Laboratory (now commercialized) known as the VISTA System.. In the summer of 1992 the system began to operate in parallel with the existing control system for beam-line element control. A set of prototype programmable tuning knobs has been received and software is being developed to allow more complete implementation for beam-line control.

Monitoring of temperatures and pressures in the cryogenic system has been implemented in the new control system. This new feature was accomplished with a minimal amount of development time providing an excellent test of the enhanced capabilities for which the new system was chosen.

*University of Sao Paulo, Brazil

b. Upgrade of Fast Tuners (K. W. Shepard, B. E. Clifft, N. Added,* G. Zinkann, G. Wiemerslage, and P. Markovich)

The rf phase-controlling fast tuner of each resonator of the ATLAS linac consists of a liquid-nitrogen-temperature, high-power rf system coupling a voltage-controlled reactance (VCX) to the resonator to provide fast tuning, and a room-temperature pulse driver which switches the PIN-diode-based VCX.

*University of Sao Paulo, Brazil, [1]N. Added, B. E. Clifft, and K. W. Shepard, 1992 Linear Accel., Conf. Proc., AECL-10728, p. 181.

A substantially improved VCX unit was developed for the positive-ion injector linac, and the rest of ATLAS is being re-fitted with the improved design.[1] This past year, all of the elements needed for VCX units for all of ATLAS have been fabricated or procured and the upgraded tuners are being installed as cryostats are opened for servicing. Four of seven ATLAS cryostats have been upgraded at this time. Early results show improved operational reliability and increased average fields during operation.

c. **Velocity Profile Upgrade** (K. W. Shepard, B. E. Clifft, G. Zinkann, G. Wiemerslage, P. Markovich)

The original velocity profile of ATLAS, designed for lighter ions, was not optimized for acceleration of uranium beams. Over the past year, in coordination with completion of the positive-ion injector (PII), five H-type split-ring resonant cavities originally designated for the spare ATLAS cryostat have been refurbished and installed on line in place of V-type split rings. This replaces cavities optimized for velocities $\beta = v/c = 0.15$ with cavities optimized for $\beta = 0.10$, and provides a more optimum configuration for the heavier beams. An additional L-type resonator was fabricated and installed in place of the first H-type resonator, with that H-type being moved downstream. Thus there are currently 10 L-type resonators rather than the original 9 in the booster linac and a total of 28 H-type resonators in the accelerator. The remaining 4 V-type units will also be replaced with H-types as described below.

Work has begun to convert four of the V-type cavities just removed to H-type cavities, which can be done at a fraction of the cost of new cavities. This will allow all of the cavities at the high-velocity end of ATLAS to be of the $\beta = 0.1$ type, and provide further performance enhancement for uranium beams by late 1993.

d. **Helium-Refrigeration System** (J. R. Specht, B. Millar, L. M. Bollinger, and J. A. Nolen)

There are several aspects of the ATLAS cryogenic system which are currently being modified or upgraded. Other improvements are planned for the coming years. Currently the capacity of the liquid-helium system is barely adequate for operation of the heaviest beams at maximum energy; the system requires frequent fine tuning and maintenance under these conditions. The output of each of the three ATLAS helium liquifiers can be increased by 20-30% by the addition of wet expansion engines. One such "wet engine" was ordered in late FY 1992 and it will arrive and be installed in 1993. We intend to purchase a second wet engine in FY 1994 and replace the least reliable of the three liquifiers with a larger capacity unit in FY 1995. This program will result in a reliable system which will be much more efficient electrically, and can easily meet the requirements of the most demanding beams.

Other modifications in progress are reduction of helium gas losses by reclaiming the gas normally lost from the resonator slow tuners, some liquid helium distribution system plumbing modifications in the booster area, and integration of new electronic pressure and temperature sensors with the ATLAS control system to permit monitoring and remote access to these parameters via the network. Also, as part of the general safety upgrades, the nitrogen gas vents are all being plumbed to the outside world.

e. **Upgrades Planned for the Near Future**

When accelerating very heavy ions such as ^{238}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 and leads to heating problems in the booster due to beam losses from the charge states not being used. The charge states with the same q/m as the guide beam has near 100% transmission, while those with lower q/m values go out of tune are lost on linac interior surfaces. Consequently, during 1993 a charge-state selector will be designed, built, and installed at the output of PII so as to be able to tune directly the ion species of interest. The location and concept of this device is indicated in Fig. II-4.

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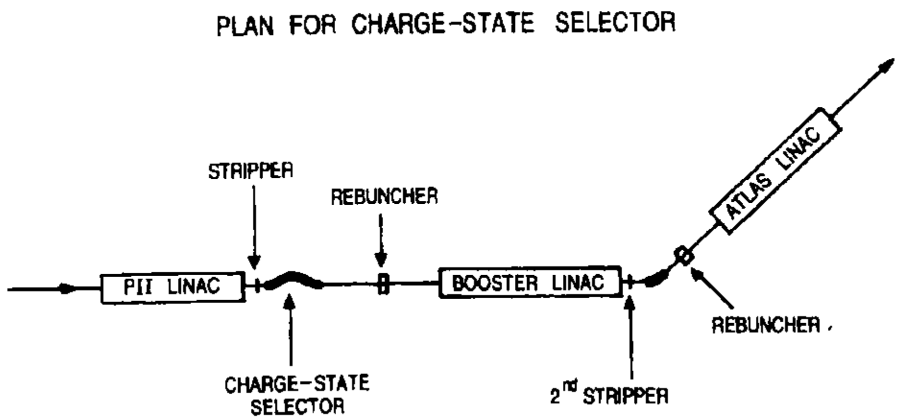

Fig. II-4. Schematic layout of the charge-state selector. This device will eliminate the need for tuning the Booster with a guide beam from the tandem, and it will also make it possible to tune ATLAS after a second stripper when necessary to reach higher energies.

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 a ^{48}Ca in normal calcium. The emittance and stability of beams such as uranium would be greatly improved because the need for stripping after PII would be eliminated by direct acceleration, e.g. of 34+ uranium ions, from the ion source. Experiments such as APEX would benefit from such an upgrade.

C. SAFETY-RELATED ACTIVITIES AT ATLAS

Several safety reviews took place during 1992, leading ultimately to the Operational Readiness Review in August. During this process many new safety sub-systems were implemented; these are summarized below in this section. In all, these systems represent several man-years of initial effort and a general increase in effort required to operate and maintain them. Some of these systems, especially ARIS and the Beam Current Monitor system, represent significant technical achievements in their own right.

a. **Radiation Interlock System** (B. B. Back, J. T. Goral, R. E. Harden, R. C. Pardo, L. M. Bollinger, M. Carpenter, K. E. Rehm, I. Ahmad, and J. P. Schiffer)

A new ATLAS Radiation Interlock System (ARIS) has been designed and implemented. ARIS was an important component of the ATLAS Safety Analysis Report and was subjected to extensive review by an independent committee. This system provides 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.

ARIS has been running continually since July and has worked very much as envisioned. The system has not exhibited failures brought about, for example, by bad weather or harsh electrical interferences encountered at ATLAS. Recently, ARIS has been augmented. The modification was to split Area IV into two separate ARIS areas. Originally, the entire area was treated as one ARIS area. Due to space limitations, it is not possible to put a shielding wall in the area to separate the two experimental stations, namely the FMA and APEX. Thus, the partitioning of Area IV was accomplished by use of infrared intrusion detectors. These detectors define a "light wall" which splits the area in two. With the light wall implemented, the two areas act independently, allowing experimenters, for example, to work at APEX while beam is delivered to the FMA, as long as the radiation detected around APEX does not exceed the limits set by ARIS.

b. <u>Beam-Current Interlock System</u> (J. Bogaty, B. E. Clifft, and L. M. Bollinger)

This system was engineered with redundant, self-checking circuitry to provide a fail-safe, completely independent safety system to limit the magnitude of a maximum credible radiation incident. Because of its potential commercial application, it has been entered in the R&D 100 contest and a patent is pending.

c. <u>Beam-Current Attenuator</u> (R. Vondrasek, R. C. Pardo, and L. M. Bollinger)

In some cases the ECR ion source puts out 10 to 100 times the current necessary for an experiment. In such cases the Beam-Current Attenuator system is used to set a firm upper limit on the intensity that could be accelerated accidentally. It does this through the use of metal mesh screens with transmission factors chosen to be appropriate for each experiment. As part of the safety procedure of each experiment, the degree of attenuation required, if any, is specified, and the screen must be locked in place before the beam can be tuned.

d. <u>Shielding</u> (J. R. Specht, L. M. Bollinger, and G. Wiemerslage)

The greater beam intensity now possible with the PII injector compared to the tandem injector has resulted in a need to increase the shielding in a few locations around the accelerator. Increased local shielding around two Faraday cups was installed to reduce possible radiation levels in publicly accessible areas. Two new water-filled shield doors have been added as well. One door is located in the 40° bend region at the end of the booster linac to reduce neutron flux which may be possible with light beams. The other water-filled shield door replaces a wire gate in the ATLAS tunnel near the first beam-line switching magnet to the experimental areas. Lead shielding was also added to cryostats C and D of the Booster linac to reduce X-ray radiation levels in this area.

e. <u>Oxygen-Deficiency Safety System</u> (S. L. Craig and R. C. Pardo)

Although the probability of asphyxiation at ATLAS from an accidental release of helium, SF_6, or liquid nitrogen is small, the risk from this hazard is being reduced further by the installation of an oxygen-deficiency detection and interlock system. Oxygen sensors were installed in a number of locations and now will alarm in the ATLAS control room in the event a low oxygen level is detected. Response procedures were formulated and staff training has occurred. In a second phase of development of this system, the alarms will be sounded locally as well as communicating to the Argonne emergency response operator. Exhaust fans and exterior doors will also be controlled by the system to speed the exhausting of any gas which has reduced the oxygen levels in sensed areas.

D. ACCELERATOR PHYSICS AND LINAC DEVELOPMENT

J. A. Nolen, R. C. Pardo, K. W. Shepard,
R. Harkewicz, K. Joh, J. Bogaty, B. Clifft, G. Zinkann,
M. Kedzie, G. Wiemerslage, and P. Markovich

This section describes the accelerator-physics program that initially developed the underlying methods which made the ATLAS facility possible. This is now an on-going program with several related goals: one is to maintain the forefront expertise of the small group who developed the technology of Nb superconducting structures for low-beta ion accelerators. The collective know-how of the Argonne team in the design, fabrication, and use of this technology is unique in the world. Another goal is to continue development as necessary in superconducting-linac-related specialties to keep ATLAS modern and competitive as a National User Facility. These related technologies include high-charge-state ion sources, beam diagnostics, accelerator-control systems, fast-timing techniques, cryogenics, and linac-beam-dynamics studies. Much of the technology of ATLAS is of increasing interest for a possible future radioactive-beam facility and some aspects of it are also potentially of industrial ignificance. Many of these accelerator-physics developments are fundamental and involve both undergraduate and Ph.D. students, as well as postdoctoral appointees and the permanent ATLAS scientific and technical staff.

Recent accomplishments and future plans for these programs are described in some detail in the following sections and are summarized here. Recent efforts were concentrated on finishing and commissioning the new positive-ion injector (PII) for ATLAS. This involved the highly successful development of a new class of 4-gap niobium accelerating structures (in four variations) useful over the ion-velocity range from 0.008c to 0.05c for ions with q/m as low as 0.1. The superconducting injector linac of PII is fed with ions from an ECR source mounted on a deck which is floated at potentials up to 350 kV. The overall system works extremely well, and together with ATLAS, has already produced CW beams of lead and uranium in the 5.5- to 6.5-MeV-per-nucleon energy range with intensities up to five particle nanoamps.

Near-term and future plans for the development program include continued development and basic studies of superconducting niobium low-beta structures, e.g. design and construction of a prototype SC-RFQ (funded by an SBIR grant), and similar work on an extended multigap structure as an evolution of the PII resonator concept. Extensions of the PII linac concepts to lower velocity and lower q/m would be quite relevant to the secondary accelerator of a radioactive-beam facility. Similarly, ECR ion-source development will be carried out with one goal being a second source and high-voltage platform for ATLAS and another being to solve the problem of simultaneous high efficiency and reasonable q/m for a radioactive-beam facility.

Other developments which are currently in progress are the design, construction, and installation of a charge-state selector between the PII and booster linacs to eliminate the need for tuning with guide beams from the tandem injector for the heaviest beams, which require stripping after PII to reach the necessary energies; and the acquisition and installation of "wet engines" as add-ons to the ATLAS helium refrigerators to both reduce electrical power usage and increase cryogenic capacity.

a. Experience with the New Positive-Ion Injector

The construction of the Positive Ion Injector (PII) was completed in the winter of 1992 and first beam was delivered from the PII on March 29, 1992. Beam tests were conducted in April and the injector and ATLAS were approved via a Preliminary Operational Readiness Review to operate in a commissioning mode which began in May. See the section 'Operation of the ATLAS Accelerator' for a discussion of the overall operating activity of the system for the research program.

The performance of the complete PII system has largely met all design goals. The ECR source performance has generally exceeded the original design goals - especially for the heaviest beams - in terms of charge state. Even so, the performance of the source should be better. A new postdoctoral position has been created to assist in source development and we hope this enhanced attention to source development will pay additional dividends soon.

The resonator field performance has also generally exceeded expectations. Accelerating fields for the PII resonators have averaged between 3.2 and 3.5 MV/m - approximately 10% above the design requirements. A problem appeared in a resonator which developed a weld crack. This problem has been repaired and is discussed further below.

The beam quality of the PII has met or exceeded our expectations. Longitudinal emittance for PII beams is generally substantially better than similar beams from the tandem injector. This is especially true for the lighter beams for which no stripping is required. Transverse beam emittance appears, as expected, to be similar to the emittance obtained from tandem beams.

Our understanding of this new injector is in its infancy and a number of components still must be constructed and installed to make the system operate more efficiently. Most important of these systems is the charge-state selector to select a particular charge state after stripping at the PII exit and a newly designed master oscillator system which will greatly expand our flexibility in matching the beam into the various major sections of the linac.

1. <u>Status and Developmental Efforts of the PII ECR Ion Source</u> (R. Harkewicz, P. J. Billquist, and R. C. Pardo)

During the past year, work on the ECR source has been directed toward (1) the development of heavy-ion beams for nuclear physics research and (2) research and development of source hardware with the purpose of enhancing and improving source performance. The source has performed during the past year without significant failure producing beams of carbon, neon, aluminum, silicon, argon, krypton, molybdenum, xenon, lead, and uranium for the experimental program. The ECR source has also been used to produce an argon beam as part of an AMS experiment to measure the isotopic abundance of the radioisotope ^{39}Ar in natural argon samples.

In a test, approximately 12 enA of $^{48}Ca^{10+}$ was produced from natural abundance (0.2%) material at the entrance to the PII linac. We believe this performance can be improved somewhat, but it is already sufficient for one particular approved experiment. It should be noted that in this same test the other calcium isotopes (^{42}Ca, ^{43}Ca, and ^{44}Ca) were observed at the PII linac entrance with beam currents of 38 enA, 8.5 enA, and 110 enA, respectively; experiments would be possible with these isotopes if requested.

The uranium beam development began using the pseudo-gas UF_6. For our first uranium beam acceleration tests in July 1992, 250-300 enA of 28+ uranium was available. For the second uranium beam test in September 1992, the ceramic uranium oxide UO_2 was used in the source which then delivered up to 500 enA of the 28+ uranium; more recently, the source produced approximately 700 enA of the 28+. It should be noted that using the UO_2 the extracted beam current from the source peaked at 24+ uranium with over 4 eμA (see Fig. II-2), and this charge state has been used in a recent APEX run.

In an effort to explore new ways to produce beams from solid materials, we are attempting to develop a laser-ablation technique for evaporating material directly into a pulsed laser and off-line tests of ablation rates for various materials are planned. If these tests appear promising, the laser will be moved to the ECR source for production tests. In addition, an independently heated low-temperature oven is being tested which will allow materials such as Li, Mg, P, K, Ca, Ti, Pb, and Bi to be introduced into the source. Experience at other laboratories seems to indicate that more stable, more intense beams of these materials can be produced using an independently heated oven as opposed to using the ECR plasma to heat and evaporate these materials (plasma heating is the current method we employ to produce beams from some of these materials with our source).

In addition, during the past year a negatively biased probe was installed and tested in the ECR source with the purpose of replacing the source first stage as a means of generating "cold" plasma electrons. Initial results of these tests appeared not very encouraging, however we are presently reviewing plans for modifying and trying this technique again, hopefully with better results. We are also conducting off-line tests with a commercially available electron gun; initial tests look promising. Plans are underway to actually test such a gun in the source.

2. <u>PII Tuning Algorithms and Bunching Efficiency</u> (R. C. Pardo)

For efficient operation of ATLAS, it is important that tuning and configuration algorithms be developed. We have chosen to operate the source and injection beam-line system in a constant velocity mode which optimally matches the acceptance of the first resonator. This new technique makes setting the bunching system from calculation possible and minimizes the need to check beam timing for every beam. This procedure was implemented in the last two months of 1992 and will soon become the operating standard. The last component required for full implementation of the system is the new master oscillator system which will enhance our ability to easily phase the major sections of ATLAS with each other.

The PII injector bunching system is performing well. Beam-bunch widths from the first stage of bunching range from 1.2 to 2.5 ns FWHM and are generally as expected from the various limiting issues as modeled in calculations. The achromatic beam-transport system is necessary for this capability and is functioning as expected. Total transmission through the PII linac is from 50-60%. This transmission reflects the bunching efficiency of approximately 60%. Therefore, the intrinsic transmission of the PII linac is 90-100% for most beams.

Beam tuning of PII is still in its infancy with essentially no automation. Fortunately the reproducibility of settings has been excellent and scaling of tunes for other beams has been possible. During this year, the standard ATLAS 'Autoscan' program will be modified for the PII and a more automatic beam-scaling program will be implemented.

In one instance we have attempted to calculate the resonator-phase settings for one beam based on the tune of a beam with a significantly different charge-to-mass ratio. Although this test was not completely successful it was tantalizingly close. We are now actively studying calibration parameters and calculation algorithms in an effort to improve the results of this approach. If successful, it would significantly improve the speed with which beams can be changed at ATLAS as well as increase the flexibility in choosing beam parameters.

3. <u>Injector Linac Components</u> (K. W. Shepard, G. Zinkann, B. E. Clifft, M. Kedzie, and G. Wiemerslage)

Resonators and Cryostats

All 18 resonators and 3 cryostats of the injector linac have been operated for extended periods of time over the past year. The injector linac uses 4 variations of the new 4-gap structures, one of which is shown for comparison with the original 3-gap structures in Fig. II-5. Performance generally has been excellent - the systems have proven reliable and straightforward to maintain and operate. Following installation of the upgraded fast tuner described below, mechanical stability has been entirely adequate, and the accelerating gradients obtained exceed the design goal of 3 MV/m. Both lead and uranium beams have been accelerated all the way through ATLAS, and PII has been used as the injector for many experiments already in FY 1993.

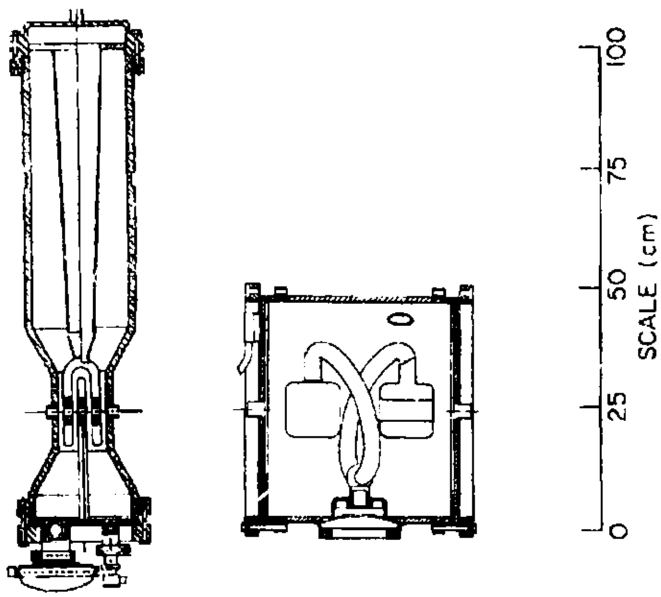

Fig. II-5. The superconducting resonators in the Booster and ATLAS Linacs are of the 3-gap, split-ring type shown on the right, while those in the new Positive-Ion Injector Linac are of the 4-gap, quarter-wave type shown on the left.

Phase Control

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. Continuing development of the VCX for PII exposed a thermal stability problem with the 4 K to 77 K thermal transition element of the 30-KW rf coupler for the VCX fast-tuner. The coupler proved to be a leading factor in limiting on-line performance to less than 3 MV/m, the PII design goal. Careful rf field mapping of the coupler led to a re-design which proved to be thermally stable at operating fields above 4 MV/m.

The upgraded VCX, with the new coupler, has been installed on all resonators in PII, and gives excellent performance, providing better phase control, higher gradients, and better reliability than was previously the case for the ATLAS linac. This result marks the successful completion of a substantial VCX development effort, required for the PII linac, but likely to be of benefit for the technology generally.

RF Control Electronics

The rf control module for the PII linac has been substantially upgraded from the earlier ATLAS version. This was motivated in part in order to handle the severe multipacting behavior exhibited by the coaxial superconducting accelerating structures employed in PII. The upgraded control module employs up-to-date rf components that permit, among other advantages, substantially higher rf gain. The increased gain enables the system to automatically drive a resonator through a weak multipacting barrier, so that the frequency with which operator intervention is required for resonator conditioning is greatly reduced. Other design changes have increased the reliability, speed, and accuracy of the rf control module, which has proven highly successful in all respects during extended operation this past year.

4. Beam Diagnostics (J. Bogaty, B. E. Clifft, and R. C. Pardo)

The fast Faraday cup (FFC) developed at Argonne, and which has been awarded a U.S. Patent, continues to be our most important diagnostic for setting up the PII-injection-bunching system. One cup is installed in the first PII cryostat (at liquid helium temperature), attached to the first resonator.

The performance of this unit in a cryogenic environment has been excellent. Demonstrated resolution of the FFC is now approximately 300 ps FWHM, so that beam-pulse widths at a fraction of this value can be inferred.

The stripline technology developed for these devices has been applied to improve the time resolution from micro-channel plate detectors for an atomic-physics experiment recently carried out by an ANL PHY group at the BNL light source.

b. Technology of RF Superconductivity

This work has several parts. One is a continuing investigation of many aspects of the basic technology of rf superconductivity (RFSC). Two activities are a part-time effort in collaboration with others to develop new kinds of low-ß accelerating structures. Also included is a beam-dynamics study aimed at upgrading and extending the options for very low-velocity accelerating structures.

1. Basic RFSC Technology Studies (K. W. Shepard, M. Kedzie, G. Wiemerslage, P. Markovich)

A resonator test facility dedicated to the study of basic RFSC was completed. A PC-based rf control and data-acquisition system, including software, was developed to the point of being useful in performing superconducting resonator tests. Experimental work, focusing initially on the phenomenon of electron multipacting in superconducting structures, began in early FY 1993. The PC-based control and data-acquisition system facilitates a variety of tests and measurements on superconducting
resonators, and has already proven beneficial both to ATLAS-related and other RFSC development and upgrade activities.

2. Beam Dynamics and Alternating Phase Focusing (J. A. Nolen, K. Joh, R. C. Pardo, and K. W. Shepard)

In early studies of the beam dynamics at the critical first few resonators of the PII linac,[1] it was noted that these 4-gap structures possess an inherent alternating phase-focusing property enabling them to be focusing simultaneously in both longitudinal- and transverse-phase spaces (see Fig. II-6). The geometrical layout of PII was not done to take advantage of this property because there were too many other unknowns about the performance of these new accelerating structures. Now that PII is completed
and excellent performance of the new systems was demonstrated, we are calculating in detail the focusing and acceptance properties of these resonators. The preliminary results of these studies, which are part of the thesis research of a graduate student in accelerator physics, indicate that extensions of the PII linac to lower velocities (less than 0.01c) could be done with extended structures (more than 4 gaps) and fewer focusing solenoids. Such concepts could be very relevant in designing a cost-effective injector for a radioactive-beam facility.

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[1]R. C. Pardo, K. W. Shepard, and M. Karls, Proc. of the 1987 IEEE Particle Accelerator Conference, Washington, DC (1987), pp. 1228.

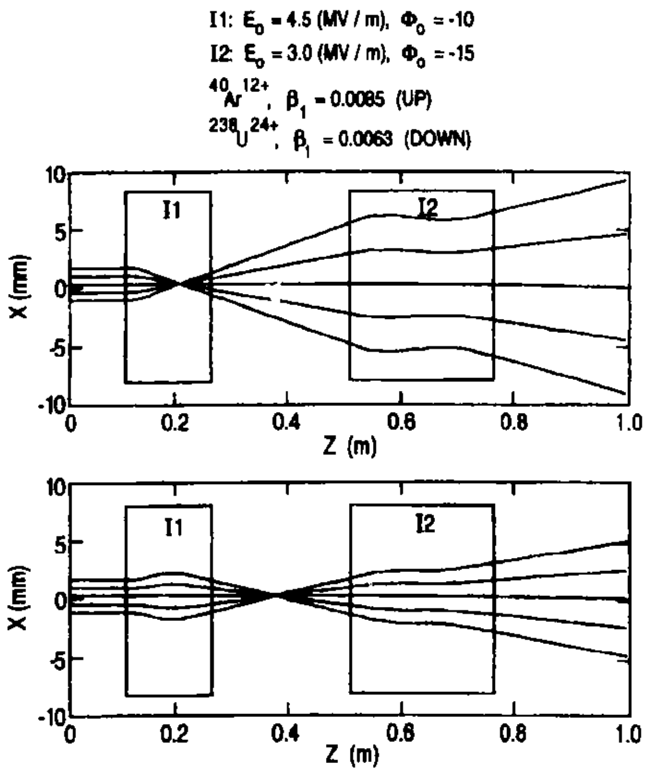

Fig. II-6. The transverse raytracing plots for $^{40}Ar^{12+}$ (up) and $^{238}U^{24+}$ (down) beams with parallel rays at the beginning. For both ions these resonators are focussing in both the transverse and longitudinal coordinators.

3. <u>Superconducting RFQ Development (SBIR)</u> (K. W. Shepard, W. L. Kennedy,* R. Hamm,† and J. M. Potter†)

The possibility of developing a niobium superconducting RFQ and testing it by accelerating a beam from ATLAS had been explored in FY 1992 through a collaboration with staff members from the ANL Engineering Physics Division resulting in a promising structure design. This led to an expanded collaboration now including AccSys, Inc. of Pleasanton, California. Work is in progress, funded through a Phase II SBIR grant, to construct and test (off-line) a prototype superconducting RFQ structure. The structure design, including considerations of beam dynamics for a possible ATLAS beam test, is complete and the first of two rounds of copper model tests were completed. Copper model tests have established that the mechanical stability of the design is adequate and that earlier numerical modeling is accurate. Niobium procurement and tooling development are underway, and fabrication was begun in the first half of FY 1993.

*Engineering Physics Division, ANL, †AccSys, Inc., Pleasanton, CA

4. Superconducting Resonators for the New Delhi Booster Linac
(K. W. Shepard, A. Roy,* and P. Potukuchi*)

Argonne has established a joint project with the Nuclear Science Centre, Delhi, India, aimed at developing improved SC resonators for use in a small heavy-ion linac. Funding for the joint project is provided entirely from New Delhi. Two staff members from the Nuclear Science Centre have been at Argonne for the past year to participate in this project, and other technology development efforts at ATLAS. A new SC accelerating structure, consisting of coupled coaxial-line cavities, has been designed and room-temperature models have been tested.[1] The structure is suitable for the velocity range 0.06 to 0.15 c. Niobium procurement is complete and prototype resonator construction began in early 1993. Prototype development is expected to be completed by June 1994. The cavity is shown in Fig. II-7.

*Nuclear Science Centre, New Delhi, India,, [1]K. W. Shepard and A. Roy, 1992 Linear Accel. Conf. Proc. AECL-10728, p. 425.

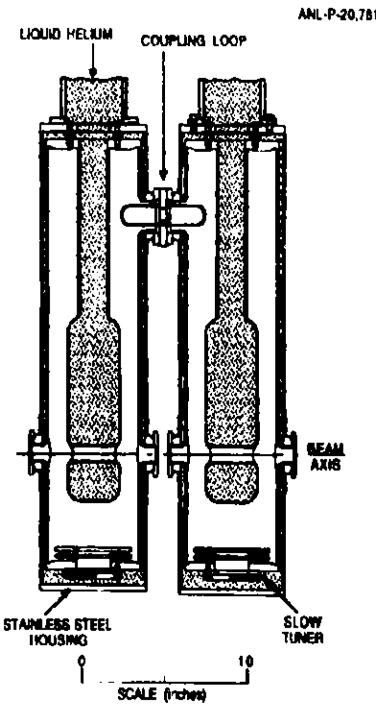

Fig. II-7. Coupled pair of 100-MHz quarter-wave coaxial-line resonant cavities. The shaded region shows the volume occupied by liquid helium. The superconducting structure is fabricated from solid niobium sheet, primarily with cylindrical symmetry; no explosion-bonded Cu-Nb material is used.

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 Argonne 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 are spokesmen for five experiments that have been approved for running 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. FY 1992 was devoted to detailed engineering of SOS and procurement of long lead items, with major fabrication beginning in FY 1993. Commissioning of SOS is planned for mid-FY 1994.

FNAL experiment E665 uses deep inelastic scattering of 490-GeV muons at the Fermi National Accelerator Laboratory to study the structure of the nucleon and its modification in nuclear matter. Observation of coincident leading hadrons is an integral element of the experiment. The very high muon energy is essential for probing deep into the shadowing region and for studying high-energy transfers where hard QCD processes are expected to be significant. Argonne members of the collaboration played a major role in the execution of the experiment and continue a strong involvement in the data-analysis phase of the experiment. Among the topics under study are the saturation of shadowing of nuclear targets at very low x, evidence for the running of the strong-coupling constant in the transverse momentum distribution of 2 jet events, exclusive vector meson production, Bose-Einstein correlations, and inclusive hadron distributions from deep inelastic scattering. Production analysis of data taken in runs during 1990 and 1991 is in progress. The Argonne group will focus on the 1990 data to study nuclear effects in deep inelastic scattering. Production analysis will require at least three years for completion.

Considerable technical resources of the medium-energy program have been devoted to developing a new technology for producing polarized hydrogen and deuterium targets, employed in electron storage rings to study spin-dependent phenomena at high momentum transfer. Current efforts are focused on the study of elastic electron-deuteron scattering to very high momentum transfer. The tensor polarization is very sensitive to sub-nucleonic effects in nuclei, most notably meson-exchange and quark effects. A collaboration between the Argonne group and a Russian group at Novosibirsk is engaged in a program of tensor polarization measurements. A polarized deuterium gas target intercepts the circulating beam of the VEPP-3 electron storage ring and the interactions of the deuterium gas with the circulating electrons are used to study polarization effects in elastic and inelastic scattering. Current efforts are focused on preparation of a laser-driven spin-exchange target designed at Argonne which will be used in the final phase of the experiment to reach largest momentum transfers. Installation of the final-phase target will begin in late 1993. At the same time, measurements are continuing at intermediate momentum transfers. The program at Novosibirsk provides a proof-of-principle for a proposal for HERMES, a broadly-based North American-European collaboration, to study the spin structure of the nucleon using internal polarized targets in the HERA electron storage ring at the DESY Laboratory, Hamburg, Germany. The HERMES proposal has been approved by the DESY directorate, and the US groups of the HERMES collaboration are organizing their participation. A proposal for US funding has been completed and submitted to DOE for review. The Argonne group will have responsibility for particle identification in the HERMES experiments and for continuing development of the laser-pumped target technology.

Activities involving the NPAS program at the Stanford Linear Accelerator Center are approaching their conclusive phase. Analysis of data from measurements of the photodisintegration of the deuteron at photon energies up to 4.2 GeV is nearing completion. In a companion experiment, a study of quasifree 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. The data show no evidence for such anomalies. A limited involvement continues in the studies at the Brookhaven National Laboratory AGS to explore global features of relativistic heavy-ion collisions under the conditions of high nuclear densities. Measurements emphasize inclusive spectra of emitted particles and two-particle correlations.

In the study of the weak interactions at low energy, the most noteworthy development was the completion of a search for a 17-keV neutrino whose existence has been the subject of intense controversy. The Argonne experiment employs a superconducting solenoidal beta spectrometer and a novel technique for reducing the effects of back-scattering. The results are conclusive. There is no evidence for a 17-keV neutrino and an upper limit on the branching ratio is below 0.25%. With the announcement of these results, proponents of the 17-keV neutrino have retracted their claims.

A. SUBNUCLEONIC EFFECTS IN NUCLEI

a. **Deep-Inelastic Muon Scattering from Nuclei with Hadron Detection** (D. Geesaman, H. Jackson, S. Kaufman, E. Kinney, V. Papavassiliou, D. Potterveld, A. Zghiche, T. Kirk,* H.J. Trost,* R. Kennedy,† H. Kobrak,† P. Madden,† A. Salvarani,† Robert A. Swanson,† A. Eskreys,‡ P. Malecki,‡ K. Eskreys,‡ K. Olkiewicz,‡ B. Pawlik,‡ B. Baller,§ G. B. Coutrakon,§ J. Hanlon,§ H. Melanson,§ H. E. Montgomery,§ J. G. Morfin,§ C. Salgado,§ S. Wolbers,§ T.. Dreyer,¶ M. Erdmann,¶ J. Hass,¶ W. Mohr,¶ H. Stier,¶ M. Wilhelm,¶ J. M. Conrad,# G. Fang,# A. Kotwal,# D. G. Michael,# R. B. Nickerson,# F. M. Pipkin,# M. Schmitt,# Richard Wilson,# M. R. Adams,** T. Carroll,** R. Guo,** C. Halliwell,** S. Magill,** D. McLeod,** S. Aid,†† S. Kunori,†† S. O'Day,†† E. J. Ramberg,†† A. Skuja,†† P. H. Steinberg,†† R. L. Talaga,†† P. Anthony,‡‡ M. D. Baker,‡‡ W. Busza,‡‡ T. Lyons,‡‡ L. Osborne,‡‡ J. Ryan,‡‡ V. Eckardt,§§ H. J. Gebauer,§§ D. Hantke,§§ G. Jansco,§§ A. Manz,§§ S. Söldner-Rembold,§§ H. J. Seyerlein,§§ P. Stopa,§§ P. Strube,§§ M. Vidal,§§, P. A. Bhatti,¶¶ R. Davisson,¶¶ W. Dougherty,¶¶ D. M. Jansen,¶¶ S. Krzywdzinski,¶¶ J. Lord,¶¶ H. J. Lubatti,¶¶ J. Wilkes,¶¶ T. Zhao,¶¶ H. Braun,## U. Ecker,## A. Röser,## S. K. Dhawan,*** V. W. Hughes,*** K. P. Schüler,***, H. Venkataramania,*** F. Dietrich,††† H. Clark,‡‡‡ K. Hicks,‡‡‡ R. Finlay,‡‡‡ K. Griffioen,§§§ P. Spentzouris,¶¶¶ and H. Schellman¶¶¶)

Deep-inelastic lepton scattering from nuclei provides a direct look at the quark structure of nuclear matter. These reactions revealed the first convincing evidence that the structure of nucleons is modified in the nuclear medium and have had profound implications on the understanding of nuclear dynamics. FNAL experiment E665, using the 490-GeV muon beams 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 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 center-of-mass hadronic energy > 25 GeV, where hard QCD processes are expected to become evident and there are little data from other deep-inelastic measurements.

The data-acquisition phase of E665 was completed in January 1992 following the third block of beam time. During the 1987-1988 run, data were accumulated at two energies: 490 GeV and 100 GeV on targets of liquid deuterium (luminosities of 2×10^{36} and 2×10^{35} muon-nucleon/cm^2 at the two energies, respectively) and gaseous xenon (7×10^{35} and 2×10^{35} muon-nucleon/cm^2, respectively). Data at 490 GeV were accumulated on a liquid-hydrogen target (7×10^{35} muon-nucleon/cm^2). In this period the target was surrounded by a streamer chamber to provide essentially 4p acceptance. During the 1990 run, luminosities of 4×10^{35} were collected on targets of hydrogen, deuterium, carbon, calcium, and lead. The targets were changed every 1-3 minutes to reduce systematic uncertainties in the target dependence. In the final 1991 running period, luminosities of 4×10^{36} were collected on hydrogen and deuterium.

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* High Energy Physics Division, ANL,†University of California, ‡Institute of Nuclear Physics, Cracow, Poland, §Fermi National Accelerator Laboratory, ¶University of Freiburg, Germany, #Harvard University, **University of Illinois, ††University of Maryland, ‡‡Massachusetts Institute of Technology, §§Max-Planck-Institute, Germany, ¶¶University of Washington, ##University of Wuppertal, Germany, **Yale University, †††Lawrence Livermore National Laboratory, ‡‡‡Ohio University, §§§University of Pennsylvania, ¶¶¶Northwestern University

The first publications of these results are now appearing in the literature. To date, eighteen students have completed Ph.D. theses on this experiment and results have been presented as invited talks at numerous conferences. Final results are available from the 1987-88 data. Four letters have been published and several manuscripts are in preparation. The notable results include the first measurement of the ratios of xenon-to-deuterium cross sections down to x values of 10^{-5}, two orders of magnitude lower in x than previous results. It is observed that the shadowing of the nuclear target saturates at x ~ 10^{-3} at the value of the ratio of cross sections observed in photoproduction experiments. The ratio of the x values at which shadowing is first seen to that at which saturation occurs is ~ 20, comparable to the ratio of the nuclear diameter to the separation of nucleon surfaces in the nucleus. Similar studies of the ratio of hydrogen and deuterium cross sections at such low x values show no evidence for significant differences (see Fig. III-1) as had been suggested by some explanations of the apparent failure of the Gottfried sum rule. (Factors of 4-5 improvement in the error bars will be possible with the 1991 data.) The relative rates of two-forward-jet events have been determined to agree with those expected from QCD. The total hadronic energy in these reactions is comparable to that in the extensive data sets from e^+e^- colliders at PEP and PETRA. An excellent example of a two-forward jet event is shown in Fig. III-2. These two-forward-jet events are produced by photon-gluon fusion (unique to photon-induced reactions) and gluon bremsstrahlung (as in the e^+e^- case) and offer a promising technique to investigate the gluon distributions in the x ~ 0.01 range. Examination of the transverse momentum of the jets shows clear evidence of the running of the strong coupling constant, as a function of momentum transfer. 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, Bose-Einstein correlations and the effects of resonance production, neutral kaon distributions and low-energy target-fragment proton and neutron distributions.

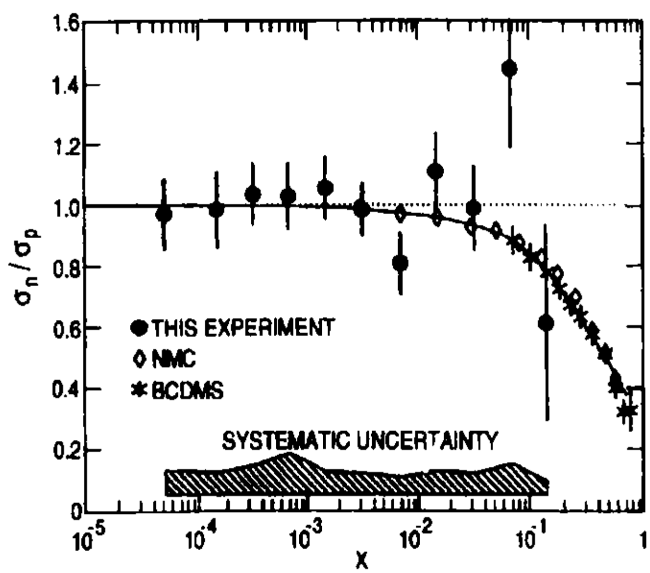

Fig. III-1. Results on s_n/s_p vs. x. The error bars show the statistical error while the shaded band shows the estimated systematic uncertainties. The curve is a theoretical prediction of Ref. 1. Also shown are previous results from NMC[2] and BCDMS[3].

[1]B. Badelek and J. Kwiecinski, Phys. Lett. B295, 263 (1992).
[2]P. Amaudruz et al., Nucl. Phys. B371, 3 (1992).
[3]A. C. Benvenuti et al., Phys. Rev. Lett. B237, 599 (1990).

Production analysis of the 1990 data is underway and the first complete results are expected to be available in the summer of 1993. Production analysis of the 1991 data should be complete by the end of the year. Argonne scientists are concentrating on expediting the production analysis, performing radiative corrections, incorporating particle identification in the analysis software, and performing the analysis at very low x. The Argonne group will continue to concentrate on the 1990 data on nuclear effects in deep inelastic scattering. Analysis efforts are expected to continue for the next three years.

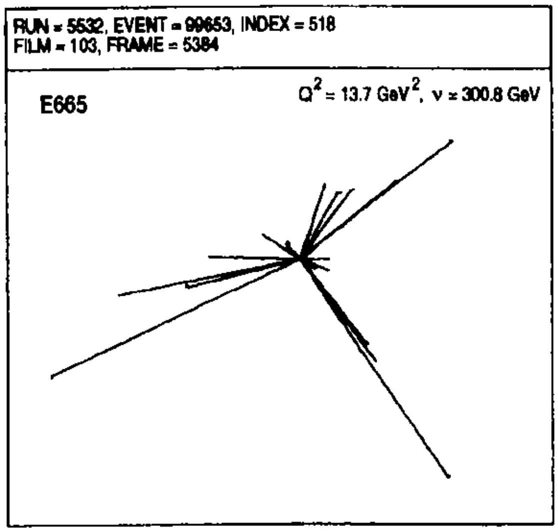

Fig. III-2. A two-forward jet event in deep inelastic muon scattering. The backward-going jet (to the left) is detected in the streamer chamber which has limited sensitivity to particles along the trajectory of the beam.

b. <u>Electron-Deuteron Scattering with a Polarized Deuterium Gas Target in the VEPP-3 Electron Storage Ring</u> (R. J. Holt, K. P. Coulter, R. Gilman, C. E. Jones, E. R. Kinney, R. Kowalczyk, D. H. Potterveld, L. Young, B. Zeidman, A. Zghiche, S. I. Mishnev,* D. M. Nikolenko,* M. Poelker, S. G. Popov,* I. A. Rachek,* A. B. Temnyhk,* D. K. Toporkov,* E. P. Tsentalovich,* D. K. Vesnovsky,* B. B. Wojtsekhowski,* K. de Jager,† H. de Vries,† and G. Retzlaff†)

An accurate measurement of T_{20} in electron-deuteron scattering is expected to provide a stringent constraint on isoscalar meson exchange currents. A high-density polarized deuterium gas target (Phase 2 storage cell), designed and constructed at Argonne, was installed and tested in the VEPP-3 ring. Results indicate that the target has a polarization $P_{zz} = 0.6 \pm 0.2$ and a thickness of 4×10^{12} nuclei/cm^2 With this target, we plan to provide T_{20} analyzing power measurements up to $Q^2 = 15$ fm^{-2}. Measurements are in progress.

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 installed in the ring and the background was reduced by a factor of four. The new collimators permit experiments to be performed at the full 200-mA electron beam at VEPP-3. A preliminary analysis of the results were performed for $Q^2 = 9.0$ and 13.0 fm^{-2}. The result at $Q^2 = 13.0$ fm^{-2} gave a much smaller absolute value of T_{20} than

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*Budker Institute for Nuclear Physics, Novosibirsk, USSR, †NIKHEF, Amsterdam expected. A more detailed analysis is under way. In anticipation of installing the laser-driven polarized target at VEPP-3, lasers and high-speed vacuum pumps were shipped to Novosibirsk recently.

c. <u>Laser-Driven Polarized Hydrogen and Deuterium Source</u> (R. J. Holt, K. P. Coulter, C. E. Jones, E. R. Kinney, R. S. Kowalczyk, M Poelker, D. H. Potterveld, L. Young, and B. Zeidman)

At present we have achieved a deuterium atomic polarization of 45% with an intensity of 8.4×10^{17} atoms/s. This represents the world's most powerful source of polarized deuterium atoms. It was possible to achieve simultaneously a high dissociation fraction and a high polarization under high throughput conditions for deuterium. The results for atomic fraction and polarization are given in panels (a) and (b) of Fig. III-3.

These results were obtained by optically pumping a thick vapor of potassium atoms which, in turn, spin exchange with the deuterium. The typical atomic ratio of posassium atoms to deuterium atoms in the spin-exchange cell was 0.01. For some experiments, this contamination of potassium, although small, is unacceptable. In order to eliminate this problem a teflon sleeve was placed in the transport tube after the spin-exchange cell. The K atoms react with the teflon and adhere to it. The teflon reduced the K atoms by a factor of five as shown in part (c) of the figure. The number of potassium atoms which reach the quadrupole mass analyzer is consistent with the direct jet from the source.

The potassium sleeve was effective a a potassium getter for more than 100 hours as shown in Fig. III-3 (c). Also, no effect on either the hydrogen polarization or recombination was observed for this length of time.

*University of Wisconsin, †Budker Institute for Nuclear Physics, Novosibirsk, USSR

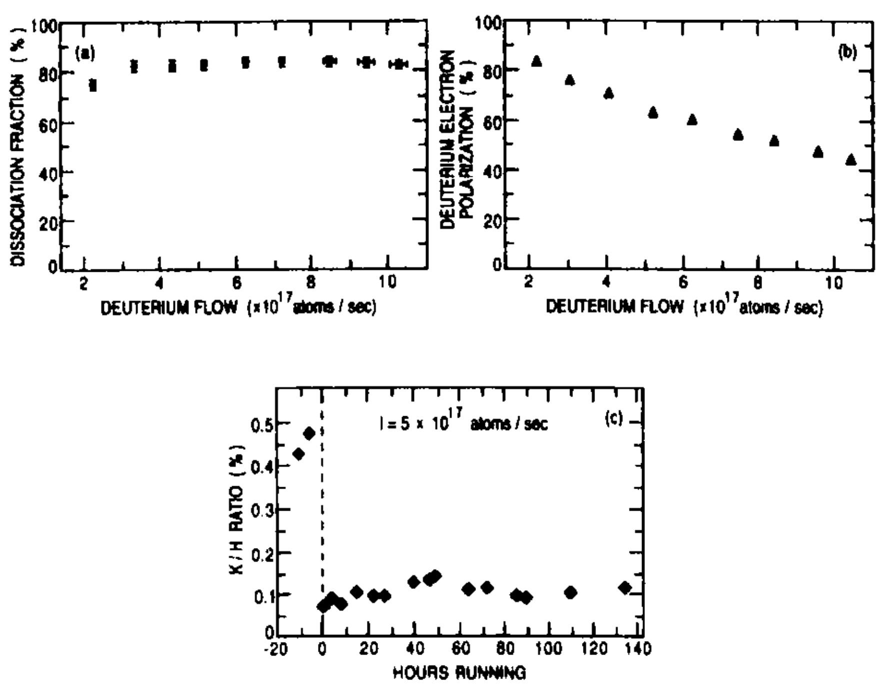

Fig. III-3. (a) Dissociation function and (b) deuterium polarization as a function of deuterium intensity. (c) Potassium-to-hydrogen ratio before and after the teflon sleeve was inserted in the transport tube.

d. **Polarized Deuterium Gas Target Polarimenter** (**R. J. Holt, K. P. Coulter, C. E. Jones, E. R. Kinney, R. S. Kowalczyk, M Poelker, D. H. Potterveld, L. Young, and B. Zeidman, J. van den Brand,* and J. Neal***)

The laser-driven polarized deuterium source is used to feed a storage cell. A teflon, potassium-getter tube is used to transport the polarized deuterium atoms to the storage cell (see Fig. III-4).

The tensor polarization P_{ZZ} of the deuterium nuclei will be measured with a polarimeter method[1] developed at the University of Wisconsin. The deuterium atoms are ionized with an electron gun, spiral in a solenoidal magnetic field toward accelerating electrodes, and collide with a tritium target in the form of a Ti ^{3}H foil. The asymmetry of the neutrons from the ^{3}H($\vec{d}$,n)^{4}He reaction is measured and the target polarization deduced using the well-known analyzing power.

At present, the Wisconsin polarimeter is being adapted to the laser-driven source. Measurements of the target P_{ZZ} should be well underway during the summer.

*University of Wisconsin
[1]J. S. Price and W. Haeberli, Nucl. Instrum. Methods A326, 416 (1993).

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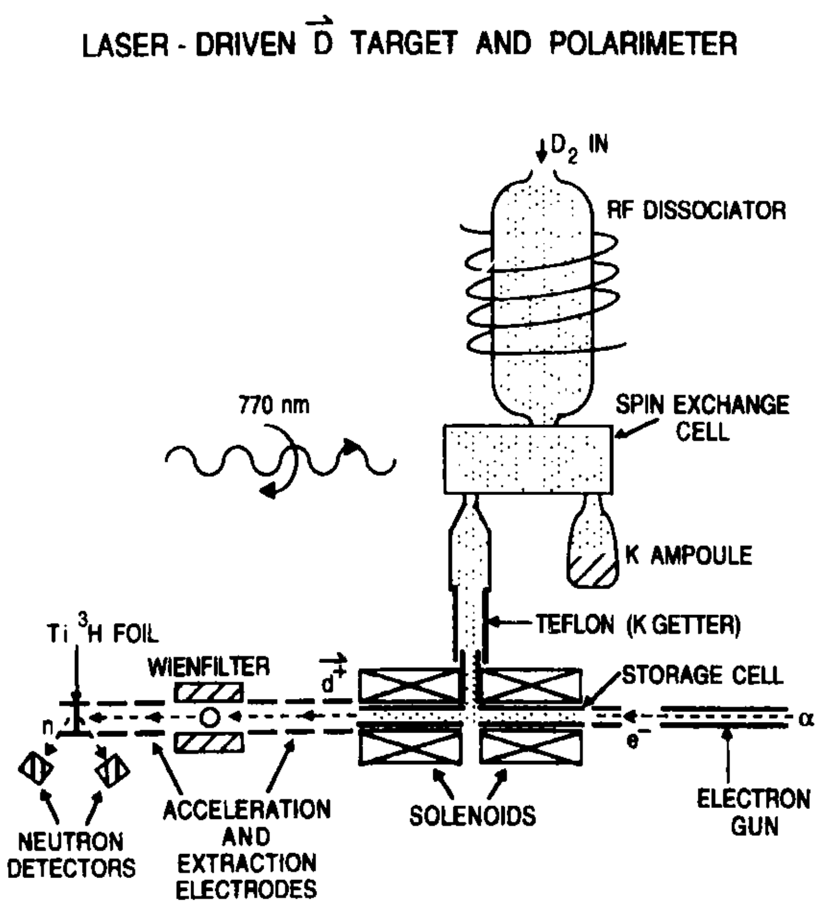

Fig. III-4. Schematic diagram of the spin-exchange source and the deuteron tensor polarimeter.

e. **Two-Body Photodisintegration of the Deuteron at High Energy: Experiment NE17 at SLAC**

(R. J. Holt, K. P. Coulter, D. F. Geesaman, H. E. Jackson, E. R. Kinney, V. Papavassiliou, D. H. Potterveld, B. Zeidman, R. Arnold,* P. Bosted,* C. Keppel,*A. Lung,* S. Rock,* M. Spengos,* L. H. Tao,* J. White,* Z. Szalata,* M. Epstein,† D. Margaziot,† J. Arrington,† E. Beise,‡ E. Belz,‡ B. Filippone,‡ H. Gao,‡ W. Lorenzon,‡ R. McKeown,‡B. Mueller,‡ T. O'Neill,‡ J. Napolitano,§ P. Anthony,¶ K. V. Bibber,¶ F. Dietrich,¶ M. Chapman,# R. Ent,# K. Lee,# N. Makins,# R. Milner,# J. Nelson,# O. Hansen,# S. Kuhn, ** Z.-E.Meziani,** G. Petratos,** R. E. Segel,†† J. van den Brand,‡‡ H. Bulten,‡‡ and C. Jones‡‡)

A preliminary analysis of experiment NE17 at SLAC was performed. During experiment NE17, data were recorded for the $\gamma d \rightarrow pn$ reaction up to a photon energy of 2.8 GeV at $\theta_{cm} = 90°$ and up to 4.2 GeV at $\theta_{cm} = 37°$. Some of the data at $\theta_{cm} = 37°$ are suspect, at present,since agreement between the photodisintegration and electrodisintegration yields is poor. However, the yields for $\theta_{cm} = 90°$ data seem to be much more consistent with one another. The preliminary cross sections at $\theta_{cm} = 90°$ for NE17 are shown in Fig. III-5. Also shown in the figure are previous data, including those[1] from experiment NE8. The NE17 result at Eg = 1.55 GeV is in excellent agreement with the NE8 data as indicated in the figure. The results at $\theta_{cm} = 90°$ continue to fall off with an approximate s^{-11} dependence expected from the constituent counting rules. Three meson-exchange calculations--Lee[2], Kong et al.[3], and Nagornyi et al.[4]--are compared with the data in Fig. III-5. The work of Lee and Kang et al. predict absolute cross sections, but the work of Nagornyi et al. is normalized arbitrarily at 1 GeV. The present work does not unambiguously rule out meson-exchange calculations.

*American University, †California State Polytechnic University, ‡California Institute of Technology, §Rensselaer Polytechnic Institute, ¶Lawrence Livermore National Laboratory, #Massachusetts Institute of Technology, **Stanford University, ††Northwestern University, ‡‡University of Wisconsin, [1]S. J. Freedman et al., "Two-Body Disintegration of the Deuteron with 0.8-1.8 GeV", ANL preprint, PHY-7504-ME-93, [2]T.-S.H. Lee, Proc. of Intl. Conf. on Medium and High Energy Nucl. Phys., May 23-27, 1988, Taipei, Taiwan (World Scientific) p. 563, [3]Y. Kang, P. Erbs, W. Pfeil, and H. Rollnik, Abstracts of Particle and Nucl. Intersections Conf., MIT, Cambridge, MA, I-40 (1990), [4]S. I. Nagornyi, Yu. A. Kasatkin, and I. K. Kirichenko, Sov. J. Nucl. Phys. 55, 189 (1992).

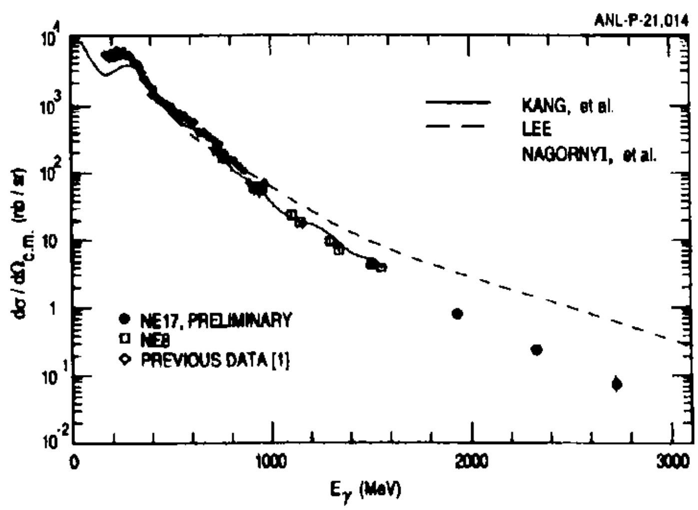

Fig. III-5. Final data from experiment NE8 are shown as the squares. Darkened circles represent the preliminary anglaysis of the NE17 data. The solid and dashed curves represent absolute calculations, while the dotted curve was normalized to the data at 1 GeV as discussed by Nagornyi et al.

f. **Nuclear and Q^2 Dependence of Quasielastic (e,e'p) Scattering at Large Momentum Transfer**
(H. E. Jackson, K. Coulter, D. F. Geesaman, R. J. Holt, E. R. Kinney, D. Potterveld, B. Zeidman, E. Beise,* B. Filippone,* W. Lorenzon,* R. Arnold,† S. Rock,† Z. Szalata,† M. Epstein,‡ J. J. Napolitano,§ R. C. Minehart,¶ R. Ent,# R. Milner,# D. Beck,** and J. van den Brand††)

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 3×10^{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 $(GeV/c)^2$. Analysis of 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 was completed during the summer of 1992. Quasielastic spectral functions were generated for deuterium and carbon. The results agree well with spectral functions obtained for the same nuclei at much lower momentum transfer, confirming the validity of the data reduction procedures and assumptions. 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 extend by over one order-of-magnitude the Q^2 range of quasielastic (e,e'p) on nuclei. Although further refinement in the analysis is expected to increase the precision of the measurements, it is already established that within ± 10%, no trend of diminished final-state interactions of the recoil proton is present. For carbon and iron targets over a momentum transfer range of 1-7 $(GeV/c)^2$ the results are consistent with the conventional Glauber approximation.

* California Institute of Technology, †American University, ‡California State University,
§ Rensselaer Polytechnic Institute, ¶University of Virginia, #Massachusetts Institute of Technology, *University of Illinois, ††University of Wisconsin

g. **Measurement of the Helicity Dependent Asymmetry in $^3\vec{He}(\vec{e},e')$ Quasielastic Scattering** (C. E. Jones, E. J. Beise,* R.W. Carr,* B. W. Filippone,* R. D. McKeown,* G. Dodson,†K. Dow,† R. Ent,† L. Kramer,† R. Milner,† D. Tieger,† P. Welch,† H. Gao,* and J.-O. Hansen†)

Measurements of the helicity-dependent asymmetry in scattering polarized electrons from polarized ^{3}He at quasielastic kinematics can provide information about the electromagnetic form factors of the neutron. Because the existing information about G_E^n, the electric form factor of the neutron, is very limited, experiments using the relatively new technology of optically-pumped polarized ^{3}He targets are generating much interest. In spring 1993 an experiment using an optically-pumped ^{3}He target developed at Caltech and a beam of 370-MeV longitudinally polarized electrons will run at the Bates electron accelerator. Inclusive

* California Institute of Technology, †Massachusetts Institute of Technology

scattering data will be collected simultaneously in two spectrometers to obtain asymmetries sensitive to both the electric and magnetic form factors of the neutron. The quasielastic asymmetry as a function of the energy transfer in the reaction will be measured over a broad range of energy transfer at 4-momentum transfer of 0.14 $(GeV/c)^2$ and 0.20 $(GeV/c)^2$. In addition, the elastic asymmetry will also be measured. Although there is existing data on the quasielastic asymmetry in this kinematic range, the statistical precision of the previous measurements is not sufficient to constrain recent theoretical calculations which give different predictions for the sensitivity of the quasielastic asymmetry to the electromagnetic properties of the neutron. The statistical and systematic precision of the proposed measurement is sufficient to provide significant experimental constraints on theoretical models.

h. **Investigation of the ^{3}He Wave Function by Quasifree Scattering** (C. E. Jones, C. Bloch,* C. D. Goodman,* W. W. Jacobs,* M. Leuschner,* H. O. Meyer,* T. Rinckel,* J. Sowinski,* F. Sperisen,* B. von Przewoski,* H. J. Bulten,† J. van den Brand,† R. Ent,‡ S. Pate,‡ W. Korsch,‡ R. G. Milner,‡ C. Tschalaer,‡ J.-O. Hansen,‡ K. Lee,‡ W. Lorenzon,¶ D. Marchlenski,# E. R. Sugerbaker,# M. Miller,† J. Neal,† O. Unal,† Z.-L. Zhou,† W. K. Pitts,†† P. Pancella,‡‡ and A. Smith*)

It was suggested that polarized ^{3}He nuclei can be used as an effective polarized neutron target because the ^{3}He nucleus is predominantly in an *S*-state where the protons couple to spin-0 and the nuclear spin is carried by the neutron. But, admixtures of *S'* and *D* states in ^{3}He dilute the effective polarization of the neutron and give a contribution from the protons to the nuclear polarization. The spin observables in $^3\vec{He}(\vec{p},2p)$ and $^3\vec{He}(\vec{p},pn)$ quasielastic scattering can provide information about the small *D* and *S'* components of the ^{3}He wave function. This information is vital for electron scattering experiments that hope to extract information about the electromagnetic properties of the neutron from polarized ^{3}He. The CE25 experiment, run at the Cooler Storage Ring of the Indiana Cyclotron Facility, will measure the target and beam analyzing powers and the spin correlation parameter in $^3\vec{He}(\vec{p},2p)$ and $^3\vec{He}(\vec{p},pn)$ quasielastic scattering. The experiment uses a polarized ^{3}He internal target developed at MIT. In 1992 a target test run was completed using 45-MeV polarized protons which demonstrated that the internal ^{3}He target has a polarization of 0.50, in agreement with optical polarimetry measurements. In a second test run, the elastic scattering spin observables were measured at 200-MeV incident proton energy. The results agree with previous measurements at the same energy made at TRIUMF. In 1993 three runs are scheduled to complete the quasielastic scattering measurements, which will be made at proton beam energies from 200 to 400 MeV. The spin-dependent momentum distribution of the nucleons in ^{3}He will be extracted. The dependence of the results upon the incident beam energy will provide information about final-state effects.

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i. **Studies of Particle Production in Collisions of Relativistic Heavy Ions with Nuclei** (S. B. Kaufman, D. Beavis,* C. Chasman,* Z. Chen,* Y. Y. Chu,* J. B. Cumming,* R. Debbe,* M. Gonin,* S. Gushue,* O. Hansen,* S. Hayashi,* M. J. LeVine,* B. Moskowitz,* J. Olness,* L. P. Remsberg,* M. J. Tannenbaum,* J. H. van Dijk,* F. Videbaek,* B. Cole,† K. Kurita,† S. Nagamiya,† P. Stankus,† O. Vossnack,† F. Wang,† Y. Wu,† W. A. Zajc,† T. Sugitate,‡ H. Crawford,§ J. Engelage,§ H. C. Britt,¶ J. Costales,¶ N. Namboodiri,¶ T. C. Sangster,¶ J. Thomas,¶ V. Cianciolo,# W. Kehoe,# D. Morrison,# S. Park,# P. Rothschild,# D. S. Woodruff,# H. Hamagaki,** R. Hayano,** S. Homma,** Y. Miake,** H. Sakurai,** S. Y. Fung,†† J. Kang,†† and R. Seto††)

The interactions of relativistic heavy ions with nuclear targets is being studied at the BNL AGS by measuring cross sections for produced particles (π,K,p) and two-particle correlations (ππ,KK,pp). Event characterization (i.e, central, peripheral, minimum bias) is done using calorimetry, charged-particle multiplicity, and transverse energy. The present experiment, E866, is the third in this series, following E802 and E859. The main objective in E866 is to measure particle production from interactions of 10.5-GeV/A Au beams with a Au target. First results were obtained in April 1992 during the commissioning of the AGS Au beam. Experiment E859 was completed just before this period, using a 14.5-GeV/A Si beam on different targets and a second-level trigger designed to enhance the recording of relatively rare, and more interesting events. These included two-particle correlations, antiprotons, K^+K^- pairs, etc. The Argonne contribution to the current experiment is limited, due to constraints of other commitments; the primary activity is to participate in the testing and calibration of phoswich scintillator arrays and a zero-degree scintillator hodoscope in collaboration with the LLNL group.

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§ University of California, ¶Lawrence Livermore National Laboratory, #Massachusetts Institute of Technology, **University of Tokyo and INS, Japan, ††University of California

j. **Electroproduction of Kaons and Light Hypernuclei at CEBAF** (K. Coulter, D. F. Geesaman, R. J. Holt, H. E. Jackson, C. E. Jones, D. H. Potterveld, S. B. Kaufman, J. P. Schiffer, V. Papavassiliou, B. Zeidman, R. E. Chrien,* S. Bart,* R. Sawafta,* R. J. Sutter,* B. W. Filippone,† W. Lorenzon,† R. Carlini,‡ D. Mack,‡ J. Napolitano,% S. A. Wood,‡ E. R. Kinney,§ O. K. Baker,¶ W. W. Buck,¶ L. Tang,¶ E. V. Hungerford,# K. Lan,# B. W. Mayes,# J. J. Reidy,** R. Ent,†† N. Makins,††, R. E. Milner,†† R. E. Segel,‡‡ A. Klein,§§ R. Gilman,¶¶ and J. F. J. van den Brand##)

Inasmuch as both the electron and K^+ are particles that interact relatively 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 D, ^{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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k. **Two-Body Photodisintegration of the Deuteron at Forward Angles and Photon Energies Between 1.5 and 4.0 GeV at CEBAF** (R. J. Holt, K. P. Coulter, S. J. Freedman, D. F. Geesaman, H. E. Jackson, S. Kaufman, E. R. Kinney, D. Krakauer, D. H. Potterveld, B. Zeidman, J. Napolitano,% R. Carlini,* R. Gilman,† R. E. Segel,‡ P. Bosted,§ E. Beise,¶ B. Filippone,¶ R. D. McKeown,¶ R. Milner,# D. Beck,** Z.-E. Meziani,†† R. Minehart,‡‡ and O. Keith Baker§§)

It was discovered in experiment NE8 at SLAC that the differential cross section for the $\gamma d \rightarrow pn$ reaction at the highest measured photon energies (E_γ = 1.3-1.8 GeV) has an energy dependence consistent with the constituent counting rules and the reduced amplitude analysis. However, the energy range of this result is too small to argue that asymptotic scaling has been achieved. During experiment NE17 at SLAC, these measurements were extended to 2.8 GeV. A preliminary analysis indicates that the s-dependence of the cross section is not consistent with constituent counting at forward angles.

At CEBAF we have proposed to measure the differential cross section at forward angles for two of the simplest exclusive binary reactions involving a deuteron in the initial or final state: (1) $\gamma d \rightarrow pn$ between E_γ = 1.5 and 4.0 GeV, and (2) $\gamma d \rightarrow \pi^0 d$ between $E\gamma$ = 1.0 and 3.0 GeV. This proposal was approved by the CEBAF PAC4.

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

% Rensselaer Polytechnic Institute, *CEBAF and College of William and Mary, †Rutgers University, ‡Northwestern University, §American University and SLAC, ¶California Institute of Technology, #Massachusetts Institute of Technology, **University of Illinois, ††Stanford University, ‡‡University of Virginia, §§Hampton University

ℓ. **A Study of Longitudinal Charged-Pion Electroproduction in D, ^{3}He, and ^{4}He at CEBAF** (H. E. Jackson, K. P. Coulter, D. F. Geesaman, R. J. Holt, S. Kaufman, D. Potterveld, B. Zeidman, R. Gilman,* E. R. Kinney,† J. Mougey,‡ B. Saghai,§ and R. E.Segel¶)

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 electro-production 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. At CEBAF, we will 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}. Measurements for a number of light nuclei will provide useful data on the

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sensitivity of longitudinal electroproduction to nuclear binding effects. If current conceptions of pion-exchange currents in nuclei are correct, longitudinal 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. 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.

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

A proposal was approved by the CEBAF PAC-5 to continue (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, Tp = 400 MeV and Tp = 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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§ Massachusetts Institute of Technology, ¶Rutgers University

n. **Measurement of Proton Polarization in the d(γ,p)n Reaction at CEBAF** (R. J. Holt, K. P. Coulter, S. J. Freedman, D. F. Geesaman, H. E. Jackson, D. Krakauer, D. H. Potterveld, B. Zeidman, E. R. Kinney,* E. Beise,† B. Filippone,† R. D. McKeown,† J. Napolitano,‡ R. Milner, § R. E. Segel,¶ D. Beatty,# R. Gilman,# C. Glashausser,# G. Kumbartzki,# R. Ransome,# Z.-E. Meziani,** and D. Beck††)

CEBAF conditionally aproved a proposal to measure angular distributions of the proton polarization for the $d(\gamma,\vec{p})nn$ 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 experiments NE8 and NE17 that perhaps asymptotic scaling has been observed above a photon energy of 1.3 GeV. Photoproton polarization measurements at lower energy indicate

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that the magnitude of the polarization increases with energy. This is consistent with the observation that polarizations are large in high-energy processes, eg. A_{nn} in pp →pp scattering or A_y in pp → p^0X. 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.

o. **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 will be required frequently. To provide this second-arm capability we are building, under contract to CEBAF, a short-orbit spectrometer, the SOS, based on a $QD\overline{D}$ design which has been developed recently at the Los Alamos Meson Physics Facility. A cutaway view of the basic elements of SOS is presented in Fig. III-6. The $QD\overline{D}$ configuration provides a large momentum acceptance, with good energy resolution and solid-angle acceptance in a very compact geometry which can meet the needs of a broad spectrum of studies appropriate for Hall C at CEBAF.

The optical design is point-to-point in both the dispersive (vertical) and the transverse (scattering) planes. For a 1-mm target spot, the first-order resolving power is approximately 2200, while the angular resolution is < 2 mr. Because of the reverse bend in the second dipole, there is a relatively small net deflection of the beam through the spectrometer, a property particularly useful for polarization measurements. Because of the strong edge-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. SOS has been designed with a spherical bearing system at the spectrometer pivot and a hydraulic lifting assembly at the rear of the spectrometer carriage which allows the system to operate up to 20° above the horizontal plane. 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.

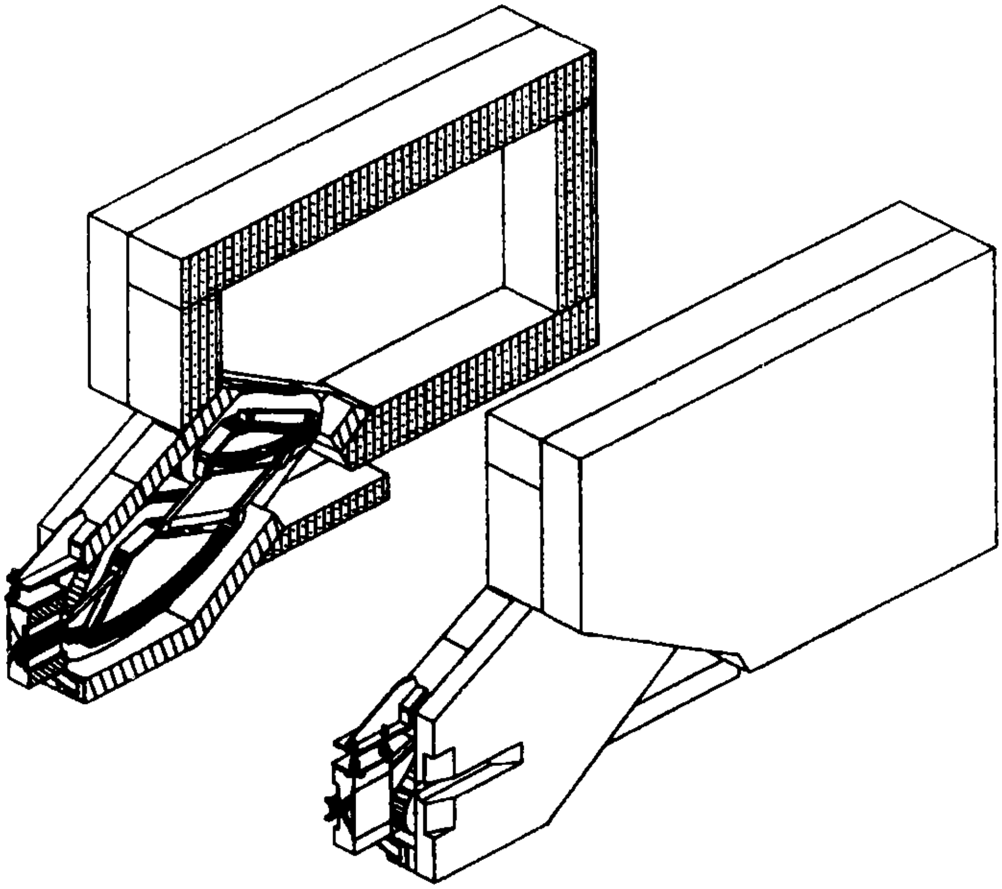

Fig. III-6. Split view of SOS Spectrometer and Detector Hut.

p. **Proposal to Measure Spin-Structure Functions and Semi-Exclusive Asymmetries for the Proton and Neutron at HERA** (K. Coulter, D. F. Geesaman, R. J. Holt. H. E. Jackson, C. E. Jones, V. Papavassiliou, M. Poelker, D. Potterveld, L. Young, B. Zeidman, P. Green,* G. Greeniaus,* Y. Ke,* P. Kitching,* N. Rodning,* E. J. Beise,† B. F. Filippone,† T. Gentile,† A. Lung,† R. D. McKeown,† M. Pitt,† E. Kinney,‡ R. Ristinen,‡ . Z. Williams,‡ W. Beckhusen,§ B. Grabowski,§ Y. Holler,§ K. Sinram,§ I. G. Bird,¶ W. Brückner,¶ M. Düren,¶ G.-G. Gaul,¶ E. Kabuβ,¶ B. Martin,¶ D. Nowotny,¶ B. Povh,¶ K. Rith,¶ C. Scholz,¶ T. Shibata,¶ E. Steffens,¶ H. Vogt,¶ K. Zapfe,¶ F. Zetsche,¶ D. H. Beck,# R. Laszewski,# C. N. Papanicolas,# S. E. Williamson,# H. J. Bulten,** J. F. J. van den Brand,** W. Haeberli,** S. Price,** T. W. K. Lee,‡‡ R. Milner,‡‡ R. Redwine,‡‡ N. Simicevic,‡‡ B. Braun,§§ G. Graw,§§ P. Schiemenz,§§ G. Burleson,¶¶ G. Kyle,¶¶ B. Park,¶¶ M.-Z. Wang,¶¶ E. Cisbani,## S. Frullani,## F. Garibaldi,## M. Jodice,## and G. M. Urciuoli##)

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

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*University of Alberta, Canada, †California Institute of Technology, ‡University of Colorado, §Deutsches Elektronen-Synchrotron, Hamburg, Germany, ¶Max-Planck Institut für Kernphysik, Germany, #University of Illinois, **University of Wisconsin, ††University of Marburg, Germany, ‡‡Massachusetts Institute of Technology, §§University of München, Germany, ¶¶New Mexico State University, ##INFN Sezione Sanita, Italy speculation that some widely accepted rules (e.g. the Bjorken and Ellis-Jaffe sum rules) may not be obeyed. The HERMES experiment is expected to provide the most accurate data for the spin-structure functions. Consequently, the HERMES experiment will provide the most accurate test of the Ellis-Jaffe and Bjorken sum rules. In addition, HERMES represents the only opportunity to obtain crucial information on the relative contribution of the valence and the sea quarks to the observed spin asymmetries. These measurements require semi-exclusive measurements which are feasible only with the pure atomic targets to be used in HERMES. Moreover, the new structure functions b(x) and $\Delta(x)$ for the deuteron will be obtained and should provide information regarding the nuclear effects on spin-structure functions. An accurate test of the Gottfried sum rule will also be measured in HERMES. This experiment involves measuring an accurate ratio of π^+ to π^- produced in deep-inelastic scattering at small x. Since no polarized targets or beam are necessary for this experiment, it probably would occur early in the program. The HERMES spectrometer is shown in Fig. III-7. The semi-exclusive measurements require good particle identification and toward that end, we are presently designing a gas Cerenkov counter for HERMES. The design is based on our experience with C1 used in E665 at Fermilab. HERMES will make use of polarized H, D and ^{3}He gas targets located in the 30-GeV HERA electron ring. The storage-cell technology for polarized gas targets which we developed for the Argonne-Novosibirk collaborative experiment (see section I.A.b.) will be employed at HERA. The experiment will also utilize longitudinally polarized electrons in the HERA ring. Now that a large transverse electron polarization ($p_e \approx 60\%$) has been observed at HERA at $E_e = 26.7$ GeV, the DESY PRC has recommended full approval of HERMES. The DESY Directorate has approved the HERMES experiment subject to successful funding of the U.S. groups. As a member of the U.S. group, we have submitted a funding proposal to the D.O.E.

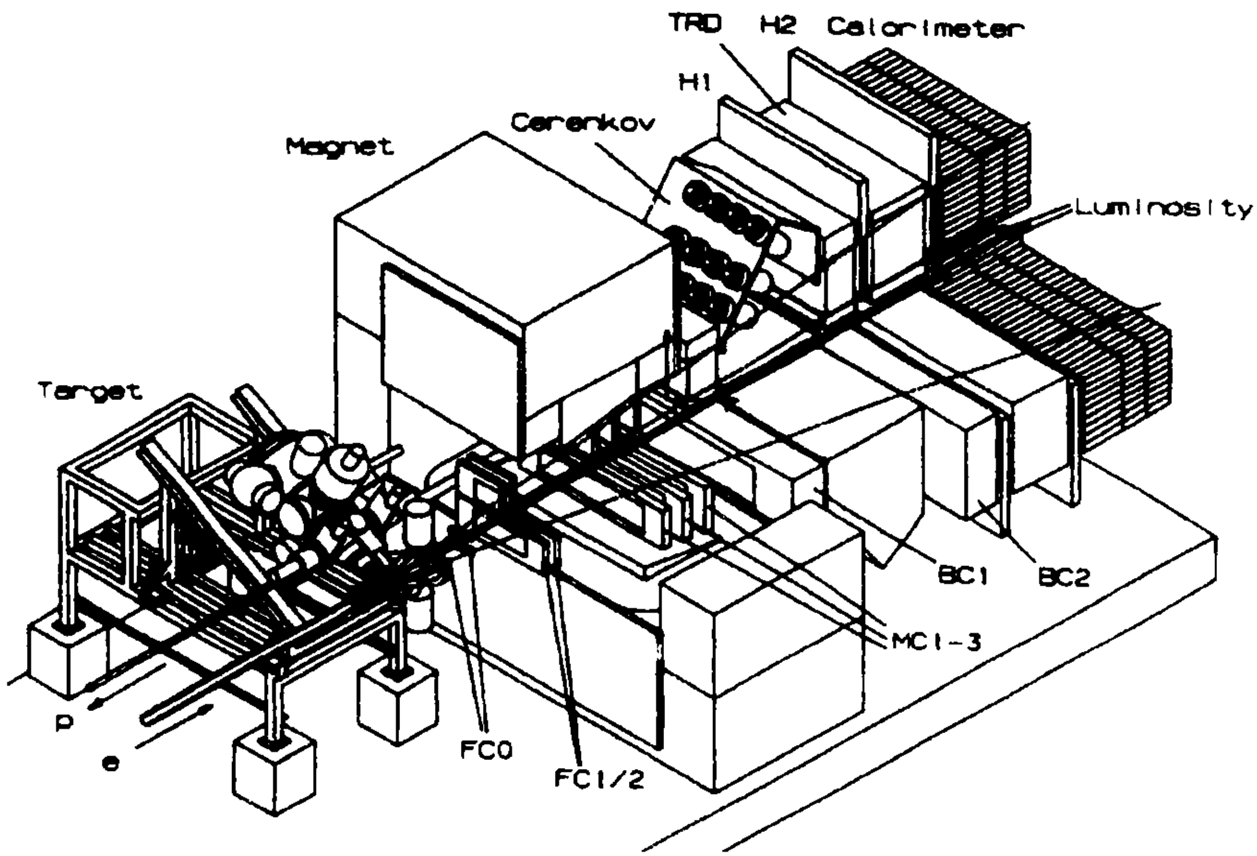

Fig. III-7. Schematic view of the HERMES spectrometer.

B. WEAK INTERACTIONS

a. The Weak-Vector Coupling and ^{10}C Superallowed Beta Decay
(S. J. Freedman,* A. Zeuli, B. Fujikawa,† and S. M. Ferguson‡)

The most precise values of the weak-vector coupling constant G_V now comes from $0^+ \rightarrow 0^+$ superallowed nuclear beta decay. In principle, the most ideal transition is the beta decay of ^{10}C because the theoretical corrections are smallest, since ^{10}C is the lowest Z nucleus which has a $0^+ \rightarrow 0^+$ superallowed branch. Unfortunately the experimental uncertainty in the beta decay branching ratio to the 0^+ excited state of ^{10}B is large. We are remeasuring this critical branching ratio at 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 γ rays following beta decay with Ge-detectors. The crucial γ-ray detector efficiency calibrations were accomplished with the $^{10}B(p,p')^{10}B^*$ reaction by observing γ rays in coincidence with inelastically-scattered protons corresponding to excitations to the 0^+ state in ^{10}B. This high precision relative γ-ray efficiency calibration was accomplished in the same geometry as was used for the beta-decay measurement.

The results of our first measurement were published in 1991 as part of M. Kroupa's Ph.D. requirement at The University of Chicago. In a more recent run we have obtained enough data to reduce the uncertainty to below 0.3%. The analysis is being completed. Data-acquisition speed is now the principal experimental limitation, but a new acquisition system, based on VMI technology was recently assembled. We believe the precision can be pushed to below the 0.1% level. This work should elucidate the apparent inconsistency of the present "best" determination of G_V with the constraint that the Kobayashi-Maskawa matrix should be unitary. Unitarity of the K-M matrix is a fundamental test of the presently constructed Electroweak Standard Model. Another run of the experiment is planned for this spring.

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*On leave at Lawrence Berkeley Laboratory, †Lawrence Berkeley Laboratory, ‡Western Michigan University

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

The decay probability for polarized neutrons could show a correlation of the form: $D(J \times p_e \cdot p_v)$. 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 2×10^{-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 are 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 electron and proton detector was tested at the NIST reactor last summer. The test was successful and proton-electron coincidences following the decay of unpolarized neutrons were detected at the expected rate. An equipment proposal for the full experiment will soon be submitted to DOE.

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*On leave at Lawrence Berkeley Laboratory

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.

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

One of the most exciting recent developments in nuclear physics is the evidence for 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 seems to occur in beta decay about 1% of the time in some experiments, others provide incompatible upper limits on the branching fraction. Last year we began a new experiment at Argonne that exploits 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. While a magnetic field is exploited in the experiment, the electron energy is measured with a solid-state detector. The 17-keV neutrino has previously only appeared in experiments with solid-state experiments and not experiments with magnetic spectrometers.

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, the detector has a resolution of better than 1 keV. We used this system to make precise measurements of the 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 has several advantages over other experiments which attempted 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 distortions from the gamma-rays that come from conversion electron sources.

The first experiment with ^{35}S beta-decay was completed this summer. We found no evidence for a 17-keV neutrino and the upper limit on the branching ratio was below 0.25% (95% cl). The experiment was checked with a mixed source of ^{35}S and ^{14}C. For this source, about 1% of the betas come from ^{14}C which is an 11-keV lower end point energy. Our experiment is able to uncover easily the distortion artificially introduced by the mixed source, proving that we should have the sensitivity to see the effect of a real 17-keV neutrino. A report of this work has been published recently. We are completing similar measurements with ^{14}C and ^{63}Ni. In addition to systematically clearing up the 17-keV issue, we plan to use the ^{14}C spectrum measurement to elucidate the influence of CVC in the mass-14 system. It turns out this provides a valuable test of CVC despite the low endpoint energies.

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*On leave at Lawrence Berkeley Laboratory, †Lawrence Berkeley Laboratory
‡Undergraduate Senior Thesis Student, University of Chicago

d. Laser Trapping of Radioactive Atoms (K. P. Coulter, S. J. Freedman,* L. Young, A. Zeuli, Z. Lu,† C. Bowers,* 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 trapped easily and manipulated with laser light. Until recently these investigations have concentrated on the physical processes of the traps themselves, and on simplifying the techniques for loading the traps. However, methods are developed well enough to be applied in various fundamental experiments.

Three 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 has been moved to the LBL 88" cyclotron at Berkeley which will be used to produce the radioactive sodium. This experiment is a first application of this technique which has other obvious applications for measuring correlation coefficients or neutrino mass. Eliminating the systematic errors associated with the usual sources in beta-decay experiments could open up a whole new area of precision measurements. Recently we demonstrated for the first time that we can cool ^{21}Na by focusing a radioactive atomic beam with laser light.

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e. Measurement of Possible Time-Reversal Non-Invariant Correlations in ^{134}Cs β–Decay (K. P. Coulter, S. J. Freedman,* B. K. Fujikawa,† and C. Bowers‡)

We began an experiment to measure time-reversal non-invariant β-γ correlations in the β-decay of optically-pumped ^{134}Cs. ^{134}Cs β-decay to ^{134}Ba proceeds between two different isospin multiplets and so the axial vector form factors may contain T-violating second-class terms, to which previous measurements were not sensitive. The presence of a term in the decay probability of the form $(\mathbf{J}\bullet\mathbf{k})^n(\mathbf{J}\bullet\mathbf{p} \times \mathbf{k})$ (where **J**, **k**, and **p** are vectors in the directions of the ^{134}Cs polarization, the β momentum and the γ momentum, respectively) would be indicative of T-violation, if it were larger than could be attributed to final-state interactions.

The experiment will make use of a sealed glass cell containing ^{134}Cs that is polarized by optical pumping. We demonstrated recently that we can polarize (polarization > 80%) dense (density ~ 5×10^{14}) samples of ordinary cesium. A buffer gas of N_2 and He was introduced to help reduce the diffusion rate and to provide a mechanism for radiationless de-excitation. We are now proceeding to apply the technique to radioactive ^{134}Cs. The sticking probability of Cs on the glass cell walls is a serious concern in experiments with radioactive atoms. This problem will be addressed in the initial measurement. An array of NaI detectors has been assembled at Berkeley and, in parallel with the optical-pumping experiments, we have begun to study the systematic errors associated with measuring the correlation.

* On leave at Lawrence Berkeley Laboratory, †Lawrence Berkeley Laboratory,
‡ University of California

f. PERKEO II: New Measurements of Neutron Decay Correlation Coefficients

(S. J. Freedman,* B. K. Fujikawa,† H. Abele,‡ J. Doehner,‡ D. Dubbers,§ and J. Last¶)

During 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 present level of the experiments. In particular, a small inconsistency between the asymmetry coefficient and the lifetime may be telling us that the weak interaction is not entirely left-handed. Even if the discrepancy disappears, these measurements may someday provide the most precise value of the vector-coupling constant. At present they give the best value of the axial-vector coupling. Our previous experiments with PERKEO done at the Institute Laue-Langevin provided values for both the lifetime and the asymmetry coefficient. About three years ago we began to develop an improved instrument for the next generation of experiments. The PERKEO II philosophy is similar to that of 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 rather than parallel as in PERKEO I.. The PERKEO II superconducting magnet is under construction at Cryomagnetics Inc. in Oak Ridge, Tennessee.

The experiment was approved to run last year at ILL but problems with the reactor demanded immediate repairs and ILL will be closed until 1994. The ILL facility is the best source of cold and ultracold neutrons in the world; its closure is a serious blow to many areas of science. As a consequence we have been forced to modify our plans. We will prepare to measure the neutrino asymmetry parameter first, before going on to the beta asymmetry parameter. This measurement can be accomplished at a lower flux reactor.

The delay in measuring the asymmetry parameter is unfortunate. There are several aspects of the fundamental theory of the weak interaction that could be better understood in the light of more precise experiments.

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¶ Institute Laue-Langevin, France

IV. THEORETICAL NUCLEAR PHYSICS

A. NUCLEAR DYNAMICS WITH SUB-NUCLEONIC DEGREES OF FREEDOM

The objective of this research program is to develop theoretical approaches for investigating the roles of mesons, nucleon resonances, and quark-gluon degrees of freedom in determining nuclear dynamics.

Theoretical models are being developed to describe nuclear dynamics in the kinematic regions where the hadronic and electromagnetic production of mesons and nucleon resonances are important. By carrying out extensive studies of πN, γN, NN and πd reactions over the years, a Hamiltonian model with π and Δ degrees of freedom was developed and applied to study various nuclear reactions induced by intermediate-energy hadronic and electromagnetic probes. The current focus is the development of a theoretical approach applicable to the energy regions accessible to CEBAF, aiming at testing various QCD-based predictions of the excitations of nucleon resonances N*.

The consequences of chiral symmetry in resolving the problems concerning the $p(e,e'\pi^0)$ and $pp \rightarrow pp\pi^0$ reactions near threshold energies have been investigated. A systematic approach to account for the short-range pion absorption mechanisms has been developed by extending Weinberg's effective πN chiral Lagrangian to nuclei.

A program has been initiated to investigate the properties of an extended meson system which is expected to be the main component of the hadronization of quark-gluon plasma.

The fundamental problems concerning the connections between relativistic particle quantum mechanics and relativistic quantum field theory have been investigated. Within a quasipotential framework, we derived the effective electromagnetic current operator for a bound two-nucleon system that is described by the Blankenbecler-Sugar equation. The light-front relativistic formulation has been applied to investigate high-energy photodisintegration of the deuteron and the spin structure functions of ^{3}He, ^{3}H.

A practical alternative to lattice gauge theory applicable in calculating hadron properties within QCD is being developed. A number of studies of QED3 and QED4 Schwinger-Dyson equations yielded valuable insight into the problem of confinement. A realistic model of a confining quark propagator was constructed and used in calculations of the pion electromagnetic form factor and the charge symmetry breaking NN forces due to the ω-ρ mixing.

A detailed study of semileptonic decays of mesons using a spectrum-generating algebra method to describe $q\bar{q}$ bound states has been carried out. Efforts are continuing in the investigation of ΛN, ΛNN and $\Lambda\Lambda$ interactions and their effects on the structure of hypernuclei.

a. <u>Hadronic and Electromagnetic Productions of Mesons and Nucleon Resonances at GeV Energies</u> (T.-S. H. Lee, K. A. Bugaev,* S. N. Yang,* and S. Nozawa†)

The objective of this work is to develop a theoretical approach for investigating the electromagnetic excitations of the nucleon resonances N* at energies accessible to CEBAF. Motivated by the existing QCD-based hadron models, 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 low-order Feynman diagrams of an effective Lagrangian with chiral symmetry.

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By employing the standard projection operator technique, a set of unitary scattering equations has been derived for describing πN and γN reactions up to the GeV energy region. As a first step, we assume that the nonresonant two-pion continuum can be approximated as a fictitious σN state. The scattering equations can then be cast into a set of coupled-channels equations involving only two-particle γN, πN, ηN, ρN, $\pi\Delta$, ωN and σN channels, which can be solved by well-developed numerical methods. The bare coupling constant and the range parameters of the form factors of hadronic vertices are adjusted to reproduce πN scattering phase shifts up to 2-GeV incident pion energy. We then explore the dependencies of the $\gamma N \rightarrow \pi N$ and N(e,e'p) observables on the $\gamma N \rightarrow N^*$ excitation strengths predicted by various QCD models of hadrons.

In 1992, we applied the approach to investigate the p-wave Roper N*(1440) resonance and the s-wave N*(1535) resonance. It was found that the πN phase-shift data in the P_{11} channel favors a bare mass of about 2000 MeV for the Roper resonance. This corresponds to a small radius of the quark core within the cloudy bag model of hadrons. A paper describing our results is being prepared. The focus of the investigation of N*(1535) is its coupling with the γN and ηN channels. We have shown that a large part of the $\gamma N \rightarrow \eta N$ cross section is due to nonresonant mechanisms involving intermediate πN and $\pi\Delta$ states. We are examining the extent to which the $\gamma N \rightarrow$ N*(1535) strength needed to describe the $\gamma N \rightarrow \eta N$ data is consistent with various constituent quark model predictions.

b. Chiral Symmetry and Threshold π^0 Electroproduction (T.-S. H. Lee, V. Bernard,* N. Kaiser,† and Ulf-G. Meissner‡)

The electroproduction of neutral pions off protons close to threshold is studied within the framework of chiral perturbation theory. The approach is based on the fundamental QCD property that at low energies the strong interactions are dictated by the spontaneously broken chiral symmetry. The calculation has been done up to the 1-loop level by carrying out order-by-order renormalization procedures. We have shown that loop effects are necessary to obtain good agreement with the recent p(e,e'π^0) data from NIKHEF. We stressed that more precise measurements, in particular of the transverse cross sections, are needed to serve as a crucial test of chiral perturbation theory. Our results are compared with data in Fig. IV-1. A paper describing our findings was published.

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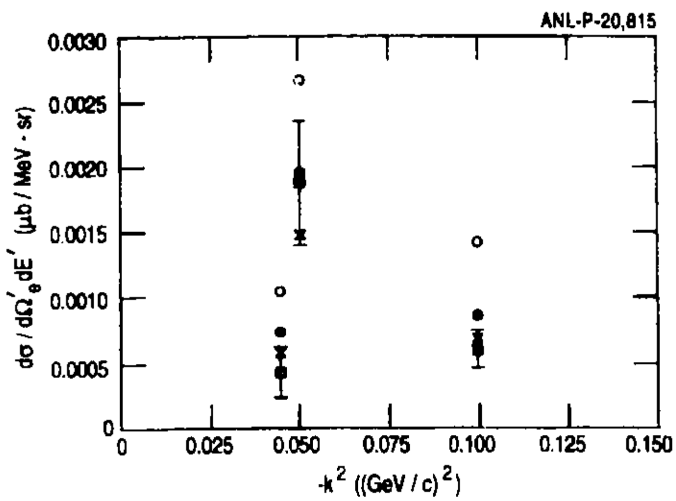

Fig. IV-1. Comparisons of NIKHEF data with the prediction from one-loop chiral perturbation theory (x) three-level (open circle) and pseudovector (solid-circle) calculations.

c. <u>Short-Range Exchange Contributions to Pion Absorption on Nuclei</u>
(T.-S. H. Lee and D. O. Riska*)

By direct extension of Weinberg's effective pion-nucleon chiral Lagrangian to nuclei, the nuclear S-wave pion production operator is described by the axial charge density operator of the two-nucleon system. It is shown that the short-range axial exchange charge operator implied by the nucleon-nucleon interaction enhances the predicted cross section for the reaction $pp \to pp\pi^0$ near threshold by factors of 3-5. This suffices to explain most of the under-prediction obtained with the single-nucleon and S-wave pion rescattering operator. The result implies that the cross section for $pp \to pp\pi^0$ can provide direct information on the short-range components of the nucleon-nucleon interaction. Our results are shown in Fig. IV-2. A paper describing our results was submitted for publication. We are extending the approach to derive the three-nucleon absorption mechanism from the existing models of three-nucleon forces.

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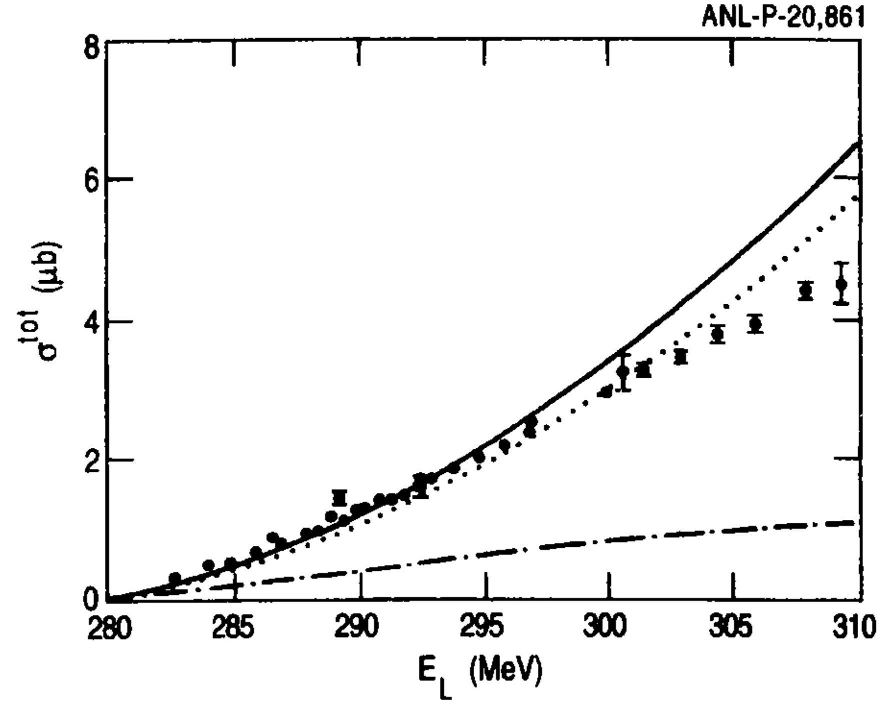

Fig. IV-2. The solid and dotted curves are respectively the total cross sections for $pp \to pp\pi^0$ using Bonn and Parrs potentials. The dot-dashed curve is obtained when a short-range axial charge operator is not included.

d. Microscopic Calculation of Inclusive (e,e') Scattering at Intermediate Energies (T.-S. H. Lee and V. Dmitriev*)

The objective of this work is to examine the extent to which the inclusive (e,e') cross section can be described in terms of the elementary $\gamma N \rightarrow N,\Delta$ processes and nuclear medium effects on the ejected nucleons and Δ's. Assuming that the propagation of the ejected nucleons and Δ's can be described by appropriate optical potentials, we have calculated the (e,e') response functions in the channel-space spanned by 1p-1h, 2p-2h and Δ-h nuclear states. The optical potentials are taken from the previous work on proton-nucleus scattering and the Δ-hole model of pion-nucleus scattering. The residual NN and NΔ interactions are accounted for in the zero-range approximation. It is found that the medium effects drastically shift the positions of the quasi-free peak and the Δ peak and reduce the magnitudes of the calculated cross sections. The importance of the two-nucleon knockout process in describing the (e,e') cross section in the "dip" region is demonstrated. The calculated ^{12}C(e,e') cross sections are in good agreement with the data in the GeV energy region. A paper describing our results is being prepared. We plan to make predictions for future CEBAF experiments.

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e Nuclear Structure Studies With the (γ,π) Reaction (T.-S. H. Lee, N. Odagawa,* H. Ohtsubo,* and T. Sato*)

The Hamiltonian model of the $\gamma N \rightarrow \pi N$ reaction developed in an Argonne-PSI-TRIUMF collaboration was applied to investigate (γ,π) reactions on 1p-shell nuclei. The calculations are being carried out by using the distorted-wave impulse approximation. The pion wave functions are generated from the Δ-hole model of pion-nucleus scattering. In a calculation for ^{14}N target nuclei, we demonstrated the importance of the πN off-shell effects and the sensitivity of the (γ,π^+) cross section to the configuration mixing in 1p-shell nuclei. To facilitate future nuclear structure studies at CEBAF, we plan to carry out extensive survey-type calculations for all 1p-shell nuclei.

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* Osaka University, Japan

f. Extended Meson System at Finite Temperature (T.-S. H. Lee and S. Landowne)

Relativistic heavy-ion collisions at the energies of the future RHIC experiments are expected to create thousands of pions along with a multitude of other particles. These pions are the main component of an extended meson system resulting from the cooling and hadronization of the predicted quark-gluon plasma. It is therefore very important to model the pions produced in such collisions. Within the finite temperature many-body theory, we have developed a self-consistent approach to calculate the properties of a thermalized self-interacting pion gas. The two essential ingredients of our approach are the assump-tion of thermal equilibrium and the π-π interaction. The latter is taken from a resonant model developed at Argonne which fits the π–π s- and p-wave phase shifts. For a specified temperature one can then calculate the effective pion potential which will modify the momentum distribution of pions at breakup. We should soon be able to obtain results for an extended pion system at temperatures accessible to the current experiments at AGS of Brookhaven and SPS of CERN. The approach will be extended to investigate the propagation of heavier mesons and to predict di-lepton production.

g. <u>Null-Plane Dynamics of Particles and Fields</u> (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 has been published. The focus of this review of null-plane dynamics is the fundamental principle of quantum theory according to which states must form a linear manifold with a unitary scalar product. The intent of this review has been to provide an integrated overview of diverse aspects of null-plane dynamics of particles and fields. Hamiltonian particle dynamics is based on the construction of nontrivial representations of 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 kinemati‿ 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. 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 consists of equivalence classes of covariant functions. The dynamics appears 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.

h. <u>Nontrivial Vacuum Structure in Light-Front Hamiltonian Dynamics of Infinite Systems</u> (F. Coester)

Systems with infinitely many degrees of freedom exhibit characteristic features and problems not present in the quantum theory of systems with finitely many degrees of freedom. While the operator algebra is independent of the dynamics, the Hilbert-space representation is dynamically determined. These features are well known for equal-time Hamiltonian dynamics where the relevant space symmetry is the Euclidean group in three dimensions and the Fock space is defined as the infinite direct sum of the Euclidean-invariant vacuum state and n-fold tensor products of Euclidean-invariant single-particle Hilbert spaces. Polynomials of creation operators applied to the vacuum state generate dense sets of Fock-space vectors. Euclidean invariant positive linear functionals over the operator algebra define vacuum states that are not in the Fock space. These linear functionals provide cyclic vectors from which inequivalent Hilbert space representations of the Fock algebra are generated. Except for coherent-state vacua there are no operators which annihilate the vacuum and satisfy canonical commutation relations with their adjoints. The Hamiltonian operators must be selfadjoint Euclidean invariant operators which annihilate the vacuum. There are many applications of the mathematical features sketched here in the quantum theory of infinite media. However the Hall-Wightman theorem precludes the construction of nontrivial equal-time Hamiltonian dynamics for relativistic quantum field theories.

In the case of Hamiltonian light-front dynamics the stability group of the light front takes the place of the Euclidean group. This change implies substantial qualitative differences from the well-known equal-time features. Since the plus components of the light-front three-momenta are restricted to non-negative values and the total momentum of a vacuum state must vanish, possible invariant positive linear functionals over the Fock algebra are far more restricted than in the equal-time case. We have demonstrated the existence of coherent-state vacua by construction. More complicated vacuum structures require the addition of explicit zero modes to the operator algebra. A paper for publication is in preparation.

i. **High-Energy Photodisintegration of the Deuteron** (F. Coester and T.-S. H. Lee)

The photodisintegration of the deuteron in light-front Hamiltonian dynamics is being investigated. The deuteron is treated as a two-nucleon system. In exploratory calculations only one-nucleon currents were included. 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 needs to include realistic final-state wave functions and exchange currents.

j. **Spin Structure Functions of ^{3}He 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. A paper for publication is in preparation.

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k. **The Electromagnetic Current Operator and the Blankenbecler-Sugar Equations** (F. Coester and D. O. Riska*)

The effective electromagnetic current operator for a bound two-nucleon system that is described by the Blankenbecler-Sugar equation has been derived. It is shown that the impulse approximation in this quasipotential framework does not satisfy the continuity equation unless explicit two-body currents are included. The minimal form for the exchange current operator that is required by current conservation is constructed, and compared to those used in phenomenological meson exchange models. A paper for publication is in preparation.

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ℓ. **Singularity Structure of a Model Quark Propagator** (C. D. Roberts, C. Burden,* and A. Williams†)

A model Schwinger-Dyson Equation (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 published.

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m. **Electromagnetic Pion Form Factor** (C. D. Roberts)

The pion is, apparently, the simplest quark-antiquark bound state. However, its nature as the Goldstone boson associated with dynamical chiral symmetry breaking in QCD significantly complicates its treatment. Notably, for example, the pion is particularly poorly described in lattice gauge theory. One of the great strengths of the Schwinger-Dyson equation approach is that it is possible to deal with quark confinement and dynamical chiral symmetry breaking on equal footing and hence the kinematic properties of the pion are very well described. Perhaps the simplest dynamical property one may consider is the electromagnetic form factor. Working in "generalized impulse approximation", in which the quark and antiquark are described by dressed propagators and the photon is assumed to interact with them via a dressed fermion-photon vertex, it is possible to obtain extremely good agreement with existing data over the entire range: q^2 = 0-4 GeV^2 and to obtain agreement with the predictions of perturbative QCD for the behaviour at large spacelike q^2. This calculation is performed using the confining model quark propagator that has been described in I.A.ℓ. The fact that the propagator is confining is crucial to the excellent agreement with experiment obtained in the calculation. Vector meson dominance plays no explicit role in this calculation. Subsequent to further exploration of the parameter dependence of this calculation and an analysis of possible implicit vector meson contributions this work will be submitted for publication.

n. **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

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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 published.

o. **Simultaneous Solution of the Coupled Fermion and Photon Schwinger-Dyson Equations in Three-dimensional Quantum Electrodynamics** (C. D. Roberts, and C. J. Burden*)

We have begun the next phase of our three-dimensional QED project: that of proceeding with the simultaneous solution of the truncated set of SDEs for the photon polarization tensor and fermion self-energy to determine if the conclusions of our earlier published investigations survive the more complete analysis. This detailed analysis will provide valuable qualitative information about QCD. Our preliminary results indicate that the self-consistent inclusion of fermion loops; i.e., going beyond the quenched approximation, weakens the interaction between fermions in the infrared but does not lead to deconfinement nor to the restoration of chiral symmetry in three-dimensional QED. At the present time the Schwinger-Dyson equation approach to QCD is insufficiently well developed for the implications of our result to be projected reliably into this domain. We continue to make progress in this direction.

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p. **Gauge Covariance and the Fermion-Photon Vertex in Three- and Four-Dimensional, Massless Quantum Electrodynamics** (C. D. Roberts and C. J. Burden*)

The crucial importance of the gauge-boson-fermion vertex to the solution of gauge field theories using the Schwinger-Dyson equations has been revealed in previous investigations. At the present time the level of sophistication is such that this vertex is unknown even in three-dimensional QED and one must model it subject to a number of elementary physical constraints. One of these constraints is gauge covariance. In the quenched approximation to three- and four- dimensional quantum electrodynamics, we have analysed the gauge covariance properties of three vertex Ansatz in the Schwinger-Dyson equation for the fermion self energy. Based on the Cornwall-Jackiw-Tomboulis effective action, it is inferred that the spectral representation used for the vertex in the "gauge technique" of Delbourgo *et al.* cannot support dynamical chiral symmetry breaking; this is, arguably, a fatal flaw. We have obtained a criterion for establishing whether a given Ansatz can confer gauge covariance upon the Schwinger-Dyson equation and demonstrated that the Curtis and Pennington Ansatz is the only one presently available that satisfies this constraint. Using our insight into gauge covariance we have been able to obtain an analytic solution of the Schwinger-Dyson equation for quenched, massless three-dimensional quantum electrodynamics for arbitrary values of the gauge parameter in the absence of dynamical chiral symmetry breaking. This work will soon be submitted for publication. The task of solving the equation for vertex itself is an important and difficult next step in this approach. We are beginning to address this problem.

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q. **ω-ρ Mixing Component of the N-N Potential** (C. D. Roberts and D. M. Flory*)

In fitting N-N phase shifts it has been found necessary to include a term in the N-N potential that can be attributed to the mixing between ω and ρ mesons that arises because of isospin asymmetry at the quark level as manifest in the small u-d current quark mass difference. To the present, this term has been assumed to be momentum independent. It is interesting to calculate this term in a covariant, confining, quark-gluon and Feynman diagram based model of QCD and compare the result with that in the existing meson exchange models. As an introduction to this calculation we studied a simple two-meson system with a Yukawa coupling. Many technical issues were resolved in this simplified system and it is planned to use the experience gained in solving the physical problem.

* Spring Semester Engineering Research Student, University of Michigan

r. **Study of Semileptonic Decays of $(q\bar{q})$ Mesons** (T.-S. H. Lee and F. Iachello*)

Semileptonic decays of mesons are a process of crucial importance for the understanding of the standard model, since they provide information on the Cabibbo-Kobayashi-Maskawa (CKW) matrix elements which are fundamental quantities of the model. Using the method of spectrum generating algebras (SGA), we have carried out a detailed study of semileptonic decays of mesons in a variety of situations. The predicted semi-analytic results for decay rates and spectral shapes can be used to extract the CKW matrix elements and/or the transition form factors from experiment. We also analyze the role of heavy quark symmetries. A paper describing our results has been submitted for publication.

* Yale University

s. **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 (π^+,pp) reactions on several targets. The calculations use the quasideuteron absorption formalism of Chant and Roos, and the two-body $\pi d \rightarrow pp$ amplitudes from Bugg et al. For $L = 0$ transitions, the target vector $\pi d \rightarrow pp$ analyzing powers are determined solely by the two-body analyzing power and are small at energies near the Δ resonance. For the general case of $L > 0$, distortion effects contribute and the analyzing powers can be quite large. A paper describing our results has been published.

* University of Maryland

t. **Effects of Correlations on $^{11}B(\pi^-,\pi^+)^{11}Li$ Reactions** (H. Esbensen, D. Kurath, and T.-S.- H. Lee)

The double charge exchange (DCX) reaction $^{11}B(\pi^-,\pi^+)^{11}Li$ is a sensitive probe of the spatial correlation between the two valence neutrons in the loosely-bound nucleus ^{11}Li. We have performed calculations of this reaction in the distorted wave impulse approximation. The closure is used to sum over all inter-mediate states in ^{11}Be. We assume that ^{11}Li consists of a ^9Li core plus two valence neutrons, and determine the associated ground state by diagonalizing a three-body ^9Li-n-n Hamiltonian, which includes an effective n-n interaction. We determine the ^{11}B-^9Li two-proton removal amplitudes from shell-model calculations. Our results show that the spatial correlation between the two valence neutrons enhances the forward-angle DCX cross section by a factor of 2 to 3 compared to the result of an independent particle description. The enhancement improves the agreement with the data considerably but the prediction is still below the data, by about 20-30%. This work has been published.[1]

[1]H. Esbensen, D. Kurath,, and T.-S. H. Lee, Phys. Lett. B287, 289 (1992).

u. **Theory Institute: Nonperturbative QCD and QCD Modelling** (T.-S. H. Lee and C. D. Roberts)

An important new direction in nuclear physics is to determine the role that quarks and gluons play in nuclear dynamics. This is also the focus of future experimental effort at CEBAF and RHIC. An important step in pursuing this research is the development of a theoretical approach to describe the quark-gluon substructure of mesons and nucleons within the framework of Quantum Chromodynamics (QCD). Presently there are three ways of approaching this problem: a) Lattice QCD; b) QCD Schwinger-Dyson Equations; and c) Modelling QCD. We conducted a one-week workshop in which approximately thirty experts in these overlapping fields were brought together. Each participant presented a 45-minute seminar and fruitful and lively discussions followed. This was the first meeting of its kind since the participants fall under different classifications within the physics community and it proved to be very timely and successful.

v. **Suppression of Λ–Σ Coupling in Hypernuclei** (A. R. Bodmer and Q. N. Usmani*)

The first careful study of the modification of the coupling between the ΛN and ΣN channels (Λ–Σ coupling) in nuclear matter was made many years ago (Bodmer and Rote 1970) by using the leading G-matrix approximation in the framework of the reaction-matrix approach. A strongly repulsive contribution was obtained which can be identified with the repulsive "dispersive" component of 3-body ΛNN forces. Subsequent work has all used the same approach but with improved potentials, with essentially the same conclusions. An essential ingredient in the reaction-matrix approach is an assumption about the single-particle spectra which also controls the neglected higher-order terms. Thus, in spite of much effort, this approach cannot be considered as giving reliable results for the Λ–Σ suppression. We are studying this problem with the Fermi hypernetted chain method. This involves only the potentials and requires no assumption about single-particle spectra, and should therefore give a much more definitive answer for the Λ–Σ suppression.

We are also continuing with studies of coupled channel and other contributions to charge symmetry breaking in the A = 4 hypernuclei ($^4_\Lambda H$,$^4_\Lambda He$).

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w. **Λ Single-Particle Energies** (A. R. Bodmer, M. Sami,* and Q. N. Usmani*)

The Λ single-particle energies B_Λ which were determined from (π^+, K^+) and (K^-, π^-) reactions on nuclei have been analyzed in a calculation based on the local density approximation. A two-body ΛN potential with an exchange component and two different forms for the three-body ΛNN potential were used in the calculation. These potentials were obtained from fits to the Λp scattering and the binding energies of the s-shell hypernuclei of ${}^{9}_{\Lambda}$Be. The ΛN exchange component which is uniquely related to the p-state interaction is very poorly determined by Λp scattering and its magnitude ε is treated as a free parameter in our fits. A Λ-nucleus potential $U_\Lambda(r)$ and an effective mass $m^*_\Lambda(r)$ are obtained by a folding procedure which uses the empirical density distribution ρ_c of the core nucleus and also makes approximate allowance for a "fringing field" due to the finite range of the ΛN force. The Λ binding energy is then obtained from the appropriate Schrödinger equation. Our analysis shows that our previously obtained interactions give a good fit to the data for the exchange parameter $\varepsilon \approx .30$ which corresponds to $m^*_\Lambda \approx 0.8\ M_\Lambda$ for the effective mass at normal nuclear density. Our analysis thus gives, for the first time, a fairly precise determination of the Λp p-wave interaction. The strongly repulsive ΛNN potential is essential for a fit to the data. The well depth is quite accurately determined to be $D_\Lambda \approx 30 \pm 1$ MeV. This work is now being completed and prepared for publication. We are considering developments which include the effects of the distortion of the core nucleus by the Λ, the inclusion of nuclear-matter-related rearrangement energy effects, and corrections to the local density approximation.

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

A one-parameter extension of the standard relativistic mean-field theory involving a self-interacting vector meson field has been investigated. We showed that such a vector meson interaction can give a large softening of the equation-of-state (EOS) of symmetric nuclear matter at large densities. A paper describing our results was published. The model has been extended to study asymmetric nuclear matter. The stability conditions take a simple form and determine the (small) proton density in terms of neutron density. This then gives a one-parameter family of neutron-star EOS which is consistent with nuclear phenomenology. We are applying this family of EOS to predict the maximum possible neutron-star mass.

y. **Scalar Aharonov-Bohm Effect** (M. Peshkin)

In a recently reported[1] experiment, unpolarized neutrons were passed through a Mach-Zehnder interferometer with different magnetic fields in the two arms. Unpolarized neutrons are an equal statistical mixture of neutrons polarized in the +z and -z directions, and the applied magnetic fields were also in the z direction. For each value of σ_z, the partial waves in the two arms have different phase shifts in traversing the two magnetic fields because of the $\mu \cdot \mathbf{B}$ interaction between the neutrons's magnetic moment and the applied magnetic field. The change in the relative phase shift can be measured when the two partial waves are recombined, and the experiment can be done in such a way that the effect does

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[1] B. E. Allman et al., Phys. Rev. Lett. 68, 2409 (1992), [2] M. Peshkin, Phys. Rev. Lett. 69, 2017 (1992)

not cancel when the two polarization states are added incoherently. This phenomenon, called scalar Aharonov-Bohm effect (SAB), was interpreted by its inventors as a new topological effect because $\mu \cdot \mathbf{B}$ is in effect a c-number in this geometry, where σ_z is a constant of the motion. The present work has demonstrated[2] that this interpretation of the experiment is misleading. Although the torque on the neutron has vanishing expectation value in a state of definite σ_z, it remains a quantum mechanical variable which connects the two polarizations states and causes μ to precess about the magnetic field **B**. The observed phenomenon exists only in the presence of a local torque and SAB is in fact not a topological effect.

B. NUCLEAR FORCES AND NUCLEAR SYSTEMS

The goal of this program is to achieve a description of nuclear systems ranging in size from the deuteron to nuclear matter and neutron stars using a single parameterization of the nuclear forces. Aspects of our program include both the construction of two- and three-nucleon potentials, and the development of many-body techniques for computing nuclear properties with these interactions. Detailed quantitative and computationally-intensive studies are essential parts of this program.

A relativistic potential which is phase-equivalent to Argonne v_{14} has been constructed and used to study corrections to the binding energy of light nuclei. The nonrelativistic Argonne potential model is being updated to incorporate charge-dependence and is being fit to the latest pp and np elastic scattering data. As this model comes on line, corresponding updates in the three-nucleon potential and electromagnetic current operators will follow.

The many-body calculations at Argonne are primarily based on the variational method with correlated operator trial functions. Parameters in the trial functions are varied to minimize the energy, and these optimized variational wave functions are then used to study other nuclear properties. The calculations can be separated into three groups, according to the size of the system: (1) direct Monte Carlo integration for few-body ($A \leq 8$) nuclei, (2) a cluster expansion with Monte Carlo integrations for larger ($8 \leq A \leq 40$) nuclei, and (3) a diagrammatic cluster expansion with integral equation summation methods for nuclear and neutron matter. Although the methods vary, the calculations are all linked by the same Hamiltonian and very similar trial functions.

Since minimization of the ground-state energy is the key to determining the wave function, much of our work has been devoted to evaluating binding energies and searching for improvements in the variational wave functions. Energies in ^{3}H and ^{4}He that are ~2% above the values from available exact methods have now been achieved. These improvements are being applied to the studies of larger nuclei like ^{6}Li and ^{16}O where the variational methods are the only practical ones at present. A very significant development this year was the evaluation of the spin-orbit splitting in ^{15}N; excellent agreement with experiment, with half the splitting coming from three-nucleon cluster contributions, has been obtained.

This year considerable effort went into calculating other nuclear properties, in particular the response to electromagnetic probes. These studies included the Euclidean response, Coulomb sum, and proton-proton correlations in few-body nuclei. A study of Δ-isobar contributions to few-body form factors and low-energy electroweak reactions was completed. Calculations of ^{16}O (e,e'p) reactions and the ground states of hypernuclei such as $_{\Lambda}^{17}$O have been initiated.

a. **Improved Nucleon-Nucleon Potential** (R. B. Wiringa and V. G. J. Stoks*)

The Argonne v_{14} potential has been the standard nonrelativistic nucleon-nucleon potential used in our many-body calculations for most of the last decade. Its chief virtue is a good fit to np elastic scattering data and deuteron properties with a simple structure that is easy to use. It contains the usual one-pion-exchange terms at long range plus a purely phenomenological part at shorter distances. It is written as a sum of fourteen operator terms, each containing a radial function $v_p(r_{12})$ multiplied by an operator. The operators are 1, $\sigma_1 \cdot \sigma_2$, S_{12}, $\mathbf{L} \cdot \mathbf{S}$, L^2 and $(\mathbf{L} \cdot \mathbf{S})^2$, and each of these times $\tau_1 \cdot \tau_2$. The fourteen radial functions are economically described with a total of 32 parameters.

The v_{14} model was fit only to np phase shifts and there have been significant improvements in the data base and phase shift analyses since the model was constructed. We are now building a new model that incorporates charge dependence and will be fit to the latest pp and np data as analyzed by the Nijmegen group. Charge dependence manifests itself most clearly in the differences bewteen pp and np scattering in $^1S_0$ states, where the scattering lengths differ by about 6 fm, and the phase shifts by several degrees through a wide range of energies. Charge dependence has been reported to contribute of the order of 200 (600) keV to the binding energy of ^3H (^4He).

The chief source of charge dependence in nucleon-nucleon interactions is the mass difference of the charged and neutral pions. The new model incorporates four additional operators (and hence is designated a v_{18} model) with an isotensor, $T_{12} = 3\tau_{1z}\tau_{2z} - \tau_1 \cdot \tau_2$, multiplying the spin operators 1, $\sigma_1 \cdot \sigma_2$, S_{12} and $\mathbf{L} \cdot \mathbf{S}$. For example, one-pion-exchange includes the charge-dependent term $1/3[v(\pi^0) - v(\pi^+)]T_{12}$, where $v(\pi)=(f^2/4\pi)(m_\pi/m_s)^2(m_\pi/3)[Y(m_\pi r)\sigma_1 \cdot \sigma_2 + T(m_\pi r)S_{12}]$ and $Y(x)$ and $T(x)$ are the usual Yukawa and tensor functions and m_s is a scaling mass. This term accounts for about half the difference in pp and np scattering lengths. The remaining scattering differences will be built into the shorter-range parts of the potential. The total number of parameters is expected to increase only to 40, with the basic structure and simplicity of the v_{14} model being preserved. The phase shift and data fitting are now in progress.

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b. **Variational Monte Carlo Calculations of Few-Body Nuclear Ground States** (R. B. Wiringa, A. Arriaga,* J. Carlson,† and V. R. Pandharipande‡)

We continue to develop our variational Monte Carlo calculations for the ground states of ^3H, ^3He, ^4He, ^5He, ^6He, and ^6Li for nuclear Hamiltonians including realistic two- and three-nucleon potentials. 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 ~3% above the best Faddeev calculations in ^3H and the Green's Function Monte Carlo (GFMC) calculations in ^4He. Effort in the last year has concentrated on improving the trial function to reduce the binding energy discrepancy with exact methods, and on increasing the efficiency of the codes.

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The Los Alamos-Iowa group has generously provided us with several of their Faddeev wave functions and we have studied the difference between these and our best three-body variational wave functions. This comparison has helped us to formulate several additional three-body correlation terms for the two-body potential in the variational wave function, reducing the discrepancy with the exact energies to ~2% in the three- and four-body nuclei. The search for additional improvements is continuing.

The current five- and six-body nuclei calculations are less satisfactory. The ^{5}He (α-n scattering) variational energies are ~6% above the available GFMC results, and the new correlations do not seem to help in this case. The ^{6}Li variational calculation currently gives a binding energy below the α, but not below a separated α-d pair, so this solution is not stable against breakup. It is not clear if this problem is due to inadequacies in the trial function or if the system is simply not stable with the Argonne v_{14} plus Urbana VIII Hamiltonian used here. Future progress depends both on the continuing search for improved trial functions in the three- and four-body nuclei, and the new potentials under development.

c. **Ground States of Larger Nuclei** (S. C. Pieper, R. Schiavilla, R. B. Wiringa, and V. R. Pandharipande*)

The methods (Sec. II.A.b.) 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 ^{16}O and other p-shell nuclei although we have made some calculations of ^{40}Ca.

This year we completed and published a large paper on the ground state of ^{16}O. It included detailed studies of the convergence of three different cluster expansions for the binding energy, which give a consistent result of 7.7 MeV/nucleon compared to the experimental value of 8.0. We also reported calculations of the nucleon density and momentum distributions, charge form factor, and longitudinal structure function.

During this year we developed a new Monte Carlo scheme for directly computing spin-orbit splitting in nuclei. This allowed us to make a complete four-body cluster calculation of the ^{15}N $p_{3/2}$- $p_{1/2}$ splitting with a statistical error of only 0.4 MeV. This error should be compared to the total binding energy of ^{15}N, 114 MeV. The result for the spin-orbit splitting is 6.4 MeV, in excellent agreement with the experimental value of 6.1 MeV. Half of this difference comes from the three-nucleon potential or from three-nucleon correlations induced by the two-nucleon potential. In addition we obtained a good value (13.7±1.3 MeV) for the proton removal energy from ^{16}O.

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d. **Nucleon, Nucleon-Cluster, Δ-Isobar and Excess Pion Momentum Distributions in Finite Nuclei** (R. B. Wiringa, R. Schiavilla, S. C. Pieper, V. R. Pandharipande,* and J. Carlson†)

The momentum distributions in ^2H, ^3He, ^4He, and ^{16}O have been computed. These include proton and neutron distributions in these four nuclei (see Fig. IV-3), deuterons in ^3He and ^4He, and tritons in ^4He. The calculations are based on correlated variational wave functions for the Argonne v_{14} two-nucleon and Urbana three-nucleon interactions. By using an improved Monte Carlo sampling procedure, the calculated nucleon momentum distribution up to 8 fm^{-1} has a much smaller variance than previously achieved. The deuteron and triton momentum distributions have also been obtained up to much higher momenta than obtained previously.

The Δ-isobar momentum distributions in ^2H, ^3He, and ^4He have also been calculated by using the Argonne v_{28} potential to build explicit Δ components into our variational wave functions. These give a total Δ-isobar content of 0.5% in ^2H and 3.1% in ^4He. The same correlations have been used to obtain improved excess-pion momentum distributions in these nuclei and in ^{16}O. A paper on this work is in preparation.

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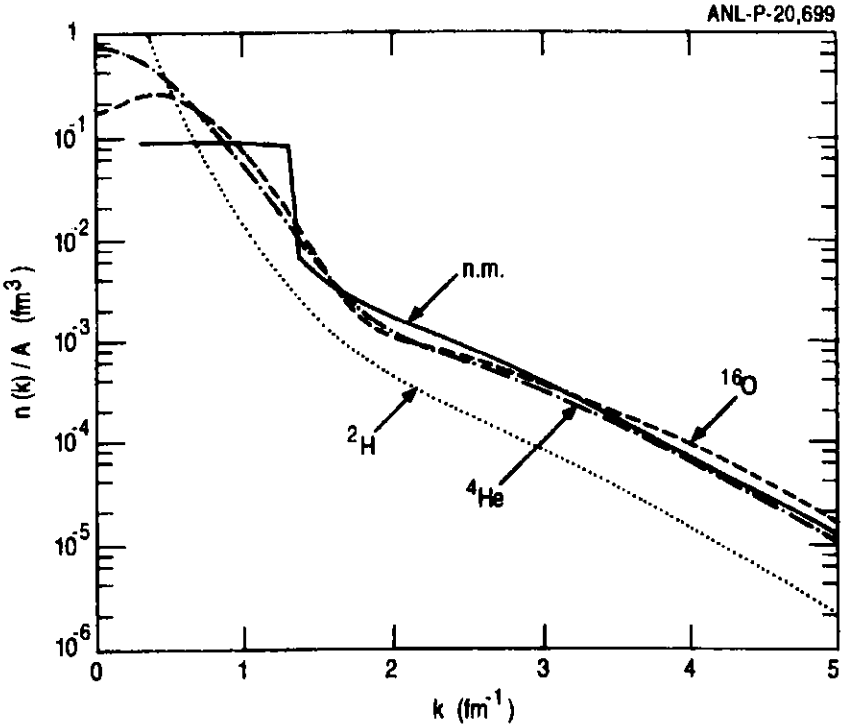

Fig. IV-3. Nucleon momentum distributions, normalized to the number of nucleons, for ^2H, ^4He, ^{16}O, and nuclear matter. Note the similarity of the large-momentum values for the last 3 cases.

e. **Relativistic Effects in Few-Nucleon Bound States** (R. Schiavilla, J. Carlson,† and V. R. Pandharipande*)

The effects of relativistic dynamics on the ground states of few-body nuclei have been investigated. These are the first calculations of both the three-body and four-body 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 previously by many groups, but actual three-body calculations are difficult and had only been done with relatively simple S-wave potentials.

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, that we 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 covariant corrections depending quadratically on the total momenta of the interacting pairs.

The Hamiltonian is 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. The relativistic effects reduce the binding energies of ^{3}H and ^{4}He by ~0.4 and 2.0 MeV, respectively. This difference is comparable to the 0.2-MeV correction in ^{3}H found by Glöckle, Lee, and Coester in 1985 using the Malfliet-Tjon interaction. We also find that the momentum distribution of nucleons is not altered significantly from the nonrelativistic case. A paper on this work has been accepted for publication.

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f. **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. The method is tested in the deuteron for a realistic potential (the Argonne v_8 model) for which the Euclidean response can be calculated exactly.

The method has been used to calculate the longitudinal Euclidean proton response in ^{4}He. This four-body calculation is 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 are in excellent agreement with those obtained by Laplace-transforming the available ^{4}He(e,e') longitudinal data from Bates and Saclay. A Letter on this work was published during the year. 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 electroexcitation operator on these response functions, and work is in progress along these lines. It should also be possible to study the imaginary time spectral function of three- and four-body nuclei with this method.

g. **<u>Coulomb Sum and Proton-Proton Correlations in Light Nuclei</u>** (R. Schiavilla, R. B. Wiringa, S. C. Pieper, and J. Carlson*)

For simple models of the nuclear charge operator, measurments of the Coulomb sum and charge form factor of a nucleus determine directly the proton-proton correlations. Experimental results for ^3H and ^3He obtained at Bates and Saclay were analyzed by Beck a few years ago and found to be in disagreement with theoretical calculations based on realistic wave functions and a one-body charge operator. The derived proton-proton correlation $\rho_{pp}(k)$ was found to have a zero at lower momentum transfer, and much greater strength in the region of the second maximum. This was interpreted as evidence for a smaller proton-proton distribution function at short distances and a stronger repulsion than current theoretical models provide. A similar discrepancy was observed earlier for the elastic electromagnetic form factors. There the theoretical calculations were brought into agreement with experiment by constructing better charge and current operators, including two-body meson-exchange contributions.

We have examined current experimental results for light nuclei from Bates and Saclay with the same charge operator used to explain successfully the charge form factor. It includes Darwin-Foldy, neutron, and spin-orbit one-body terms, and π, ρ, and ω exchanges and other two-body terms. Because of these additional terms, it is more appropriate to consider the determination of a longitudinal-longitudinal correlation $\rho_{LL}(k)$. To obtain ρ_{LL} from experiment it is necessary to measure both the charge form factor F_L and Coulomb sum S_L. An important step in forming the Coulomb sum is to estimate the unobserved strength in the longitudinal response beyond the maximum energy loss that is measured. This has been done by requiring the experimental and theoretical energy-weighted sum rules to match.

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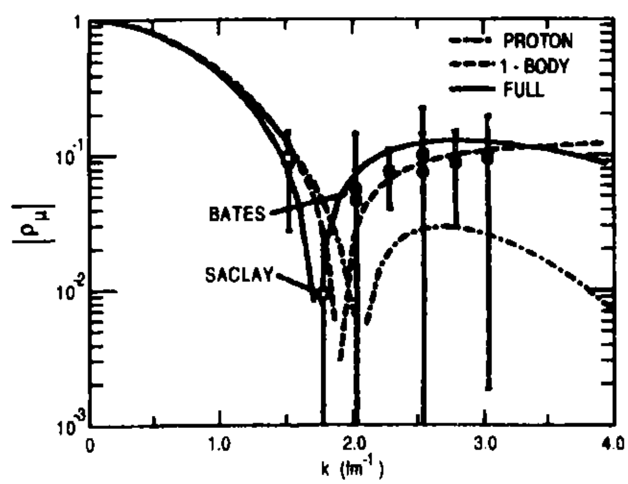

Fig. IV-4. Computed and experimental $\rho_{LL}(k)$ for ^4He. The solid curve contains both one- and two-body contributions; the dashed curve has all one-body terms; and the dash-dot curve has just the proton contributions.

We find that the extracted and theoretical results for $\rho_{LL}(k)$ in ^{3}He and ^{4}He (see Fig. IV-4) are in excellent agreement, but there is some discrepancy in ^{3}H. We conclude that due to the complicated nature of the coupling between a longitudinal photon and the nucleus, even at low momentum transfers, the ρ_{LL} extracted from (e,e') inclusive data cannot provide direct information on the strength of the proton-proton repulsive interaction at short range. A paper on this work is being prepared for publication. We are currently extending these calculations to ^{16}O.

h. Effects of Δ-isobar Degrees of Freedom on Low-Energy Electroweak Transitions in Few-Body Nuclei (R. Schiavilla, R. B. Wiringa, J. Carlson*, and V. R. Pandharipande†)

The explicit Δ-isobar components have been incorporated in few-body nuclei to study their effect on various low-energy electroweak transitions, including the trinucleon magnetic moments, the β-decay Gamow-Teller matrix element of ^{3}H, thermal neutron capture on ^{3}He, and low-energy proton weak capture on ^{3}He. The Δ-isobar components are generated by acting on our standard correlated variational wave functions with transition correlation operators that make NN→NΔ and NN→ΔΔ 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 Δ-isobar degrees of freedom.

The explicit Δ-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. A paper on this work was published during the year.

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i. Monte Carlo Calculations of (e,e'p) Reactions (S. C. Pieper, V. R. Pandharipande*, and M. Radici†)

A collaboration has been initiated to carry out detailed calculations of ^{16}O(e,e'p) reactions for which there is precise NIKHEF data. We will use final-state wave functions containing a product of the distorted wave, the variational ^{15}N wave function, and non-central correlations between the ejected proton and the nucleons in ^{15}N. The Pavia group has provided a subroutine that generates the distorted wave which is suitable for use in the Argonne nuclear Monte Carlo program. During this year we will be incorporating this subroutine into the program and writing the routines to add the NN and NNN correlations and to evaluate the expectation values of the electromagnetic current operators.

The $p_{3/2}$ quasi-hole wave function in ^{16}O has also been computed and used in the Pavia (e,e'p) program. These calculations have been made with both the conventional proton-nucleus optical potentials and with optical potentials that have been modified to include the correlation effects used in our previous study of nuclear transparency. We find that the

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quasi-hole wave function is significantly different from the mean-field wave function and that most of this difference arises from center-of-mass corrections. The correlation-corrected optical potential also results in significantly different predictions of the (e,e'p) cross secions. The first uses of the full (e,e'p) calculation will be to see to what extent such calculations can be reproduced by "single-nucleon" calculations using some form of quasi-hole wave function.

j. <u>Ground State of Hypernuclei</u> (S. C. Pieper, A. Usmani *, and Q. N. Usmani*)

The variational Monte Carlo calculation of nuclei (Secs. II.A.b and II.A.c) is being adapted for hypernuclei such as $\Lambda^{17}O$, $\Lambda^{16}O$, and $\Lambda^{12}C$. In this calculation we will use the same realistic nuclear Hamiltonians we use for normal nuclei with the addition of phenomenological NΛ and NNΛ 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 NΛ non-central correlations.

The development work for these calculations is being done principally by A. Usmani and Q. N. Usmani at Jamia Millia. We anticipate that final production calculations will be done on the NERSC computers. During the last fiscal year, most of the necessary modifications of the program were made and debugged. Pieper will spend January 1993, at Jamia Millia during which time the debugging of the program will be completed and initial three-body cluster calculations will begin. These calculations should be adequate to show the importance of various non-central ΛN correlations. Travel and living expenses are being provided by an NSF grant.

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k. <u>Nuclear and Neutron Matter Studies</u> (R. B. Wiringa, A. Fabrocini,* and V. R. Pandharipande†)

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 potentials, was completed in 1988. This work, coupled with our studies of finite nuclei, showed that the addition of plausible three-nucleon potentials can make a significant improvement in calculated binding energies and saturation properties. Subsequent calculations in finite nuclei have benefitted significantly from the introduction of three-body correlations for the three-body potential. We are now investigating ways to introduce such correlations in our matter calculations. The ^{16}O calculations (Sec. II.A.c) have also pointed out a possible discrepancy in the evaluation of L-dependent potential contributions in matter that we are now reviewing.

Future work in nuclear/neutron matter depends partly on progress in the nucleon-nucleon interaction and calculations in few-body and light nuclei. The ongoing development of an improved nucleon-nucleon potential (Sec. II.A.a) will require a refitting of the three-nucleon potential to the binding energies of light nuclei and nuclear matter saturation. The investigation of relativistic effects in few-body nuclei (Sec. II.A.d) might also be extended to matter, but the algorithm for evaluating relativistic kinetic energy will need some modification. The relativistic corrections would be of particular interest for dense matter and neutron stars.

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ℓ. **Solid-Liquid Interface in Helium** (S. C. Pieper, S. Fantoni*, and A. Belic†)

A collaboration has been initiated to investigate the solid-liquid interface in helium (both ^{3}He and ^{4}He) using the variational Monte Carlo method with shadow wave functions. Several years ago Pandharipande, Pieper, and Wiringa developed a program for Monte Carlo calculations of the ground states of drops of liquid helium. This program was a "warm-up exercise" for the nuclear program described in Sec II.A.c, but was used to produce a number of interesting results. Recently Fantoni proposed that this program could be modified to incorporate the shadow wave function of M. Kalos. Pieper spent July 1992 in Trieste to start the collaboration. Belic and Fantoni were introduced to the program and the modifications necessary to use shadow wave functions for drops of liquid helium were completed. Preliminary results indicate that such wave functions do not produce improved variational energies compared to those that were obtained by Pandharipande, Pieper and Wiringa. Belic and Fantoni will be making the necessary changes to the geometry that the program deals with to allow the study of an interface.

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C. HEAVY-ION REACTIONS

The structure of nuclei far from stability has become an integral part of this research program. This new direction is closely related to ongoing experimental heavy-ion programs and the radioactive beam facility being considered. A 3-body model for neutron-rich nuclei has been applied to investigate fragmentation reactions involving the nucleus ^{11}Li. It appears that the model provides a very good description of most of the reaction data that have been obtained up till now. The parity inversion in N = 7 isotones has been studied. A simple neutron-core Hamiltonian model to describe the low-lying positive-parity states has been developed.

The studies of heavy-on reactions at energies close to the Coulomb barrier are based on applications of the coupled-channels technique. The objective is to obtain a consistent, unified, quantum-mechanical explanation of fusion, elastic and inelastic scattering, transfer reactions and compound nucleus spin distributions. The calculations are constrained by the nuclear structure properties of the two interacting nuclei.

a. **Fragmentation Reactions of ^{11}Li** (H. Esbensen and G. F. Bertsch*)

A three-body model has been applied to calculate the ^{11}Li fragmentation cross sections that have been measured at 800 MeV/u for different targets. The eikonal approximation, which is based on free nucleon-nucleon cross sections, is used to calculate the nuclear part of the fragmentation. This approach is quite reliable at the high beam energy considered here, and our calculations reproduce the data rather well (see Fig. IV-5).

A particularly sensitive probe of the spatial correlation between the two valence neutrons is the (^{11}Li,^{9}Li) reaction, which is dominated by Coulomb dissociation for a heavy target like lead. It has been found that the spatial correlation between the two valence neutrons enhances the Coulomb dissociation cross section by more than 50% compared to the result of an independent particle description. The nuclear part of the reaction, on the other hand, is only slightly reduced. This work has been published.[1]

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*Institute of Nuclear Theory, University of Washington, [1]H. Esbensen and G. F. Bertsch, Phys. Rev. C 46, 1552 (1992).

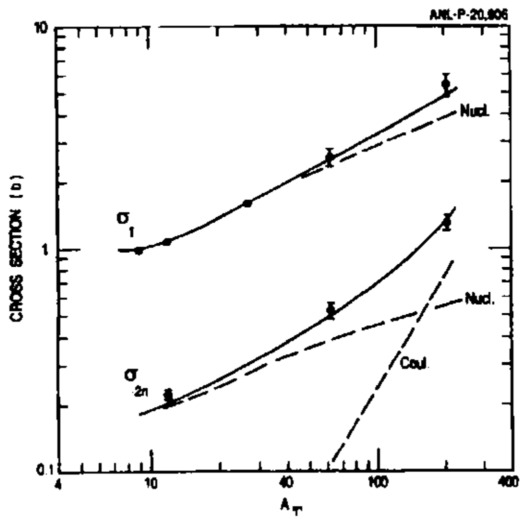

Fig. IV-5. Interaction cross sections (σ_I) and two-neutron removal cross sections (σ_{-2n}) for ^{11}Li at 800 MeV/u as a function of the target mass. The contributions from nuclear breakup are shown by the dashed lines (Nucl.). Also shown is the contribution from Coulomb dissociation (Coul.) to the two-neutron removal. The data are from T. Kobayashi et al., Phys. Lett. B232, 51(1989).

b. Momentum Distributions for (^{11}Li,^{9}Li+n+n) 3-Body Breakup Reactions

(H. Esbensen, G. F. Bertsch,* and K. Ieki†)

The first coincidence measurements of the three-body (^{11}Li,^{9}Li+n+n) breakup reaction have now been analyzed. The data were obtained at Michigan State University at a beam energy of 28 MeV/u on a lead target, and they provide the most detailed test of our three-body model for ^{11}Li. Coulomb dissociation dominates the breakup reaction on the heavy target, and our calculations are based on this reaction mechanism. The calculated momentum distribution for the relative motion of the two emitted neutrons is in remarkably good agreement with the data, and so is the single-neutron momentum distribution. The recoil momentum distribution of the ^{9}Li fragment, on the other hand, is shifted to higher momenta compared to our prediction. The measured decay energy spectrum, and the extracted dipole strength distribution are also shifted towards higher excitations compared to our predictions. These shifts are most likely due to the fluctuations generated by the post-acceleration effect, whereas the momentum distribution for the relative motion of the two emitted neutrons is insensitive to this effect (see Fig. IV-6). A paper describing our results is in preparation.

In order to resolve the discrepancies with the data it is clearly necessary to include the post-acceleration effect in the calculation. This will require a more detailed study or modeling of the decay of the excited ^{11}Li nucleus.

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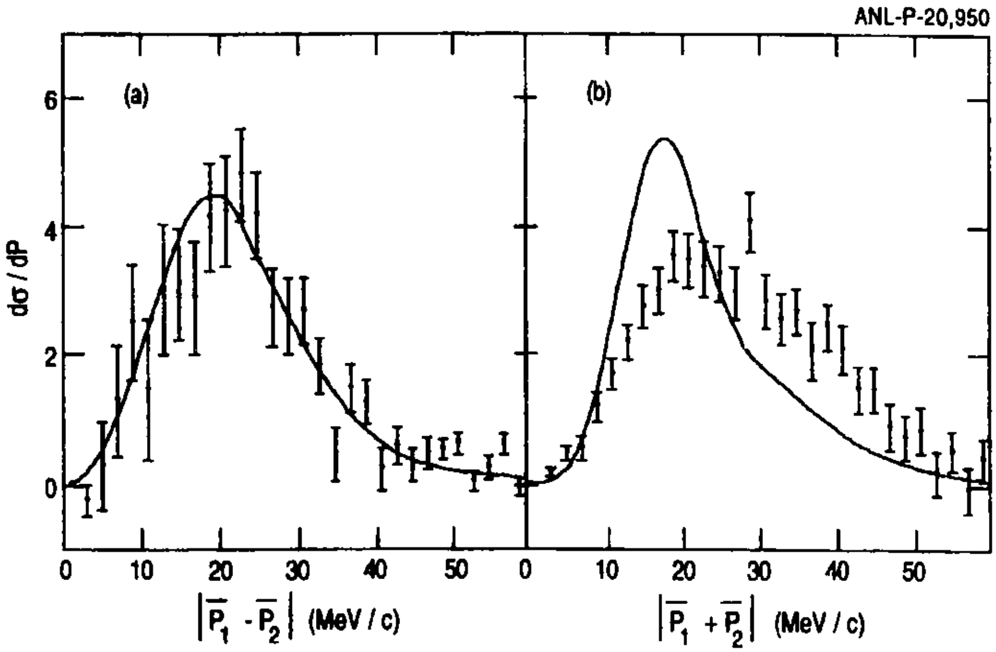

Fig. IV-6. Momentum distribuitions for the relative motion of the two neutrons (a) and the ^{9}Li recoil (b) in the rest frame of the $^{11}Li \rightarrow {}^{9}Li+n+n$ breakup reaction on lead at 28 MeV/u. The calculated curves include the detection efficiency of the measurements performed by D. Sackett et al. at Michigan State University.

c. **Parity Inversion in the N=7 Isotones and the Pairing Blocking Effect**
(H. Esbensen, H. Sagawa* and B. A. Brown†)

The basic mechanism, which is responsible for the parity inversion in ^{11}Be, has been an open question for many years; the ground state is a $1/2^{+}$ state, whereas the naive shell model would predict it to be a $1/2^{-}$ state. This phenomenon has been investigated within a shell model developed recently in which the effective NN interactions were adjusted to reproduce the binding and excitation energies in the A = 10-22 mass region.

We find that the combination of the Pauli blocking effect and a strong coupling to the quadrupole core excitation is responsible for the inversion. The Pauli pairing blocking pushes the $1/2^{-}$ state up in energy relative to the $1/2^{+}$ state, whereas the $1/2^{+}$ state is lowered by a coupling to the excited 2^{+} core state. The dominant components of the $1/2^{+}$ ground state can be viewed as a linear combination of a $s_{1/2}$ single-particle state coupled to the 0^{+} ground state of the core and a $d_{5/2}$ state coupled to the 2^{+} excited state of the core. The shell-model calculation suggests that the amplitude for the $s_{1/2}$ component is in fair agreement with the measured spectroscopic factor.

The effect of the Pauli blocking is similar in the nucleus ^{13}C. However, the single-particle energy gap is larger and the coupling to the 2^{+} core excitation is weaker, so the final result is a $1/2^{-}$ ground state. The nucleus ^{9}He may have an inverted parity spectrum due to a stronger effect of the pairing blocking. This work has been submitted for publication.

* University of Tokyo, Japan, †Michigan State University

d. **Positive-Parity States in N = 7 Nuclei** (H. Esbensen, H. Sagawa,* and B. A. Brown†)

A study of the parity inversion in ^{11}Be suggests that the positive-parity spectra of N = 7 isotones may be described in terms of a simple neutron-core Hamiltonian, which includes a quadrupole nuclear coupling between the valence neutron and a deformed core. The negative-parity spectra, on the other hand, are affected by the Pauli blocking, and the simple model would therefore not apply.

We have developed such a model Hamiltonian, with a quadrupole coupling strength that is consistent with the measured B(E2) values. The model describes the low-lying positive-parity states in ^{11}Be and ^{13}C rather well. The ^{13}C spectrum is consistent with an oblate deformation of the core, whereas the ^{11}Be spectrum favors a prolate deformation. The $1/2^+$ ground-state wave function that we obtain for ^{11}Be consists mainly of an $s_{1/2}$ single-particle state coupled to the 0^+ ground state of the core (81%), and a $d_{5/2}$ state coupled to the excited 2^+ core state (15%), consistent with the measured spectroscopic factor and shell-model calculations. There are still some minor discrepancies in the comparison to the measured low-lying, positive parity spectra. We intend to include the effect of the deformed spin-orbit interaction, and hope that it will resolve some of the discrepancies.

We have applied the model to investigate the differential cross section for neutrons emitted in the (^{11}Be,^{10}Be) breakup reaction, which has recently been measured at GANIL. This work has been submitted for publication as part of the analysis of the measurement.

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* University of Tokyo, Japan, †Michigan State University

e. **Compound Nucleus Spin Distributions in Ni+Ni Fusion Reactions** (S. Landowne)

The original measurements of ^{58}Ni + ^{58,64}Ni and ^{64}Ni + ^{64}Ni fusion reactions at sub-barrier energies opened up a new era in the study of nuclear fusion processes. Not only were the observed low-energy fusion rates orders of magnitude greater than conventional model predictions, but also the energy dependence of the ^{58}Ni + ^{64}Ni cross section differed significantly from that of the symmetric reaction partners. Our coupled-channels calculations succeeded in describing the Ni+Ni fusion data, simultaneously with the available elastic scattering and direct reaction data. The presence of direct two-neutron transfer to positive Q-value channels in the ^{58}Ni + ^{64}Ni calculation plays a key role in explaining the difference with respect to the symmetric fusion reactions. Recently, the Legnaro group has obtained some results for the compound nucleus spin distributions resulting from low-energy ^{64}Ni + ^{58,64}Ni fusion reactions. Our coupled-channels calculations have been repeated to obtain theoretical predictions. The comparison to the preliminary data shows good agreement with the shape of the observations as a function of energy but not with the absolute magnitude. The shape is notably different from conventional predictions. The calculations for ^{58}Ni + ^{64}Ni show a distinct structure in the average spin value due specifically to the direct, positive Q-value two-neutron transfer channels. The experimental uncertainty, however, is too large to test this prediction at this time. The unpublished data are currently being further analyzed by the Legnaro group.

D. NUCLEAR STRUCTURE STUDIES

The thrust of this research program is the development of an understanding of the features of nuclear structure that arise from the strong correlations due to the nucleon-nucleon interactions.

Theoretical approaches are being developed to investigate superdeformation at low and high spins and to explain phenomena associated with superdeformation such as new regions of superdeformation, rotational moments of inertia, and the transitions from superdeformed to normal states. The density dependence of residual interactions and the structure of the heaviest elements have been investigated.

The Strutinsky method calculations in the A = 180 region including a necking degree of freedom in addition to the usual quadrupole and hexadecapole deformations have been carried out. These calculations suggest that it is possible to use heavy-ion reactions to populate states that are even more deformed than have been observed so far.

In an attempt to understand identical moments of inertia in rotational bands of different nuclei both deformed and superdeformed, pairing correlations have been included in a many-body calculation. The effects of a density-dependent pairing interaction on the spectroscopic features of superdeformed states are also being examined.

The shell-model interpretations of electromagnetic properties of ^{8}Li and the fusion resonance in ^{5}He and ^{5}Li have been obtained successfully.

a. <u>Very Extended Nuclear Shapes Near A = 180</u> (R. R. Chasman)

In the past few years, superdeformed shapes have been found at high spins in the A = 150 and the A = 190 mass regions. In the A = 150 mass region, the superdeformed shapes are characterized by an axis ratio of 1.9:1. In the A = 190 region, superdeformed shapes were predicted in our calculations and were confirmed in the experiments at ATLAS. These nuclides have axis ratios of ~ 1.6:1.

An interesting open question is whether there are other regions of nuclei having superdeformed isomers that are accessible at high spins. A particularly intriguing possibility is that there may exist accessible high-spin isomers that are even more extended than those that have been seen until now. To investigate this possibility, we have carried out a series of cranked Strutinsky calculations in a three-dimensional axially symmetric deformation space. Two of the dimensions are the usual quadrupole and hexadecapole deformations; the third is a necking-in deformation which is expected to be important for very extended shapes. With the advent of very fast vectorizing supercomputers, it is now feasible to make extensive investigations of a three-dimensional deformation space. We found that the usual two-dimensional deformation space (quadrupole+hexadecapole) does not provide a useful description of energy surfaces at large deformation. Our calculations show that there is a group of nuclei near A = 180, in which isomers with very extended shapes (axis ratios of 2.2:1) might be populated in heavy-ion reactions. The best candidate nucleus is ^{182}Os. The effect of the necking degree of freedom is quite important for these nuclei, making the very extended minimum become yrast at L ~ 60h, rather than at L ~ 70h, as would be the case if the necking degree of freedom were not included. Our calculations were extended to very large elongations and to examine the magnitudes of the barriers of these extended minima against fission. In the best cases, we find barriers of ~ 9 MeV against fission at the angular momenta that the extended shapes become yrast. Heavy-ion studies of nuclei in the A = 180 region will be undertaken by the experimental group at Argonne. This work has been submitted for publication recently.

We have also found several isomers that are even more extended, characterized by axis ratios ranging from 2.5:1 to as much as 3:1. In these cases, the barriers against fission are small and it seems unlikely that such states can be populated in heavy-ion reactions.

b. **Moments of Inertia of Rotational Bands** (R.R. Chasman)

An unexpected result that has been found in the experimental investigation of superdeformed rotational bands is the observation of near identical moments of inertia in different nuclei. This phenomenon has also been noted in normally deformed rotational bands. This has motivated us to undertake a many-body calculation of moments of inertia, going beyond the usual BCS treatment of pairing correlations. A priori, the BCS method is suspect for the treatment of superdeformed nuclear shapes because the single-particle level density near the nuclear surface is small. If it were large, there would be no superdeformed minimum. We are developing a treatment of rotation using many-body wave functions with good particle number to see to what extent the BCS treatment of pairing distorts the calculation of moments of inertia in the rotational bands of superdeformed nuclei. We plan to apply this approach to a study of the superdeformed bands that have been observed in the A = 190 mass region. We are in the process of modifying our many-body code to allow for the breakdown of J_z as a good quantum number; i.e. for finite cranking frequencies.

A fundamental question concerning residual interactions is their density-dependence. Our analysis of the normally deformed actinides suggests that the pairing interaction is strongest in regions of low nucleon density. Any such effects should be even larger in superdeformed nuclei. We are investigating density-dependent interactions in superdeformed nuclei.

c. **Non-Axially Symmetric Deformation Modes** (R. R. Chasman)

Although our calculations predicted correctly 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. One possible explanation of this observation is that there are new deformation modes that lower the energy of the superdeformed minimum. We have investigated this possiblity by considering the Y(3,1) deformation mode. The multipole operator (r^3)Y(3,1) connects states that differ by two quanta in the z-direction and one in the perpendicular direction. Therefore, the Y(3,1) deformation mode might be important for superdeformed shapes. Carrying out calculations in the region near Hg, 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. We are looking into the effects of other axially asymmetric modes on the total energy surface at high spin. These calculations are quite time consuming, as there are no good quantum numbers, such as parity or signature, to reduce the size of the matrices that must be diagonalized. The calculation is further complicated by the fact that the Hamiltonian is complex.

d. The FDSM and Superdeformation Near A = 220 (R. R. Chasman)

The fermion dynamic symmetry model (FDSM) provides a group theoretical approach to nuclear structure problems. The model treats pairing and quadrupole interactions in a somewhat schematic way. Recently, the valence space handled in this approach has been extended to cover two shells and the extended model has been applied to investigate superdeformation. A most interesting prediction of this model 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 of nuclides in this region. We do not find oblate superdeformed minima in this region, but we do find oblate superdeformed minima in slightly heavier nuclides. This region of oblate superdeformation is centered at ^{222}Np; i.e. Z = 93, N = 129. This is in rather good agreement with the FDSM predictions. The oblate minima are at 7-MeV excitation energy at I = 0 and remain about 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, and found that the prolate superdeformed states do not become yrast at high spin. In fact E^* increases slightly with increasing spin. This will make the prolate superdeformed states hard to populate. We have completed this study of superdeformation in the A = 220 region and the results have been published.

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 the shell corrections near N = 184 are the $h_{11/2}$, $j_{13/2}$ and $k_{17/2}$ 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. Our analysis of low-lying states in ^{251}Cf associated with the observed (d,p) spectrum has been published. We expect to see the high-j states in a $(\alpha,{}^{3}He)$ study. The $(\alpha,{}^{3}He)$ experiment has been approved, and will be carried out in the summer of 1993.

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* University. of Kentucky

f. Nuclear Equilibrium Shapes Near A=100 (R. R. Chasman)

We have carried out a study of the A = 100 mass region in the framework of 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. This is a contradiction with the experimental fact that large equilibrium deformations are known to be present in A = 100 nuclei. 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. Detailed spectroscopic studies, which are now being carried out by I. Ahmad and collaborators at Argonne, should provide useful constraints on the pairing matrix elements.

We are also investigating the effects of a density dependent pairing force on spectroscopic features of nuclei in this mass region at low rotational frequency. Our 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 ($\gamma = 30$ degrees) 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. This is supported by the recent experimental studies of transition lifetimes by the groups in Julich and Budapest.

g. Many-Body Wave Functions (R. R. Chasman)

In the past few years, we have developed many-body variational wave functions that 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 in dealing with a nucleus that has several different minima in the energy surface. With the product structure of our wave functions, it is possible to include all particle-hole configurations with a fixed value of Jz in the many-body variational wave functions. 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 $70 < N < 184$. We can effectively increase the size of this basis by constructing basis states that are linear combinations of wave functions which include single-particle states from many higher shells. In this way we retain the orthogonality of basis states. We do however give up the orthonormality of the basis functions with different values of the generator coordinate. The extension of our many-body code to accommodate this feature implies a major coding effort. We are continuing this effort. We are also extending this many-body program to include a cranking term, in order to study rotational moments of inertia.

h. Electromagnetic Properties of ^{8}Li (D.Kurath)

Most electromagnetic measurements in ^{8}Li agree well with shell-model values, but a recently reported BE2 value between the ground state and first excited state is much larger than calculation. A study was carried out to see whether there is another shell-model solution consistent with all the observed electromagnetic properties. Although it is possible to double the calculated BE2 value, that is still at least 5 times weaker than is observed. This remains the only E2 transition in the 1p shell which greatly exceeds the shell-model value obtained by including the effective charges (ep = 1.5e, en = 0.5e) normally used. An article has been submitted for publication.

i. The Fusion Resonance in ^{5}He, ^{5}Li (D.Kurath)

A narrow resonance near 16.7 MeV in the A = 5 system is formed by the capture of low-energy deuterons by A = 3 targets. Measurements with polarized deuterons have determined analyzing powers. These have been interpreted with a resonating group model (RGM) as being L=0 capture with two possible channel spin solutions for this J = 3/2+ resonance, one of which is a nearly pure S = 3/2 channel. The shell model also has J = 3/2+ as its lowest positive-parity solution. This solution has been transformed to the channel spin representation, and it is found to be dominated by an S = 3/2 component representing a deuteron-like pair of 1p nucleons coupled to a triton-like $(0s)^3$ core. Thus such a solution also explains the main features observed in these polarization experiments. The result has been published.[1]

[1]D. Kurath, Phys. Rev. C 47, 1306 (1993).

ATOMIC AND MOLECULAR PHYSICS RESEARCH

This year, Atomic Physics focussed on research programs in the Physics Division in two principal sections:

(1) Accelerator-based atomic physics, (2) Synchrotron radiation-based atomic physics.

The accelerator-based atomic physics program is increasingly focussed around experiments at the newly upgraded ATLAS system, and its major goals are atomic-structure studies. The two other heavy-ion programs utilize the BLASE accelerator for atomic-structure studies, and the Coulomb-explosion program at the Dynamitron for molecular-structure measurements. These two programs have had reduced emphasis since September 1992, due to two different reasons: the BLASE program has a temporary reduction in effort during Linda Young's one-year leave of absence on a Fellowship at JILA in Boulder, Colorado, until September 1993; the Dynamitron-based Coulomb-explosion program has been reduced in effort for financial reasons such that operation of the Dynamitron has been limited to 2 months during FY 1993.

The program of synchrotron-radiation-based atomic-physics measurements was initiated through funds provided by Argonne Laboratory management, as part of an initiative in support of the 7 GeV Advanced Photon Source (APS) at Argonne. The latter is now under construction and is expected to be available for experiments at the end of 1995. The initial goal was to gain expertise in this exciting new area of X-ray atomic physics. The calendar year 1992 was spent partly in experiments at the Brookhaven National Synchrotron Light Source, where we share the use of the X-24A beam line and operation with the National Institute of Science and Technology (NIST). The other emphasis of the synchrotron-radiation-based work is the design and development of beam lines at the APS. We have collaborated with several University and National Laboratory groups in experiments mainly at the Brookhaven National Synchrotron Light Source (NSLS) X-ray ring. Staff expertise, especially in X-ray optics and X-ray spectroscopy, gives an additional breadth to this program.

There is strong overlap between the goals of our ongoing heavy-ion experiments testing relativistic atomic structure, and X-ray interactions with relativistic inner-shell electrons of heavy atoms. The electromagnetic interactions governing relativistic many-body systems continue to provide a fertile testing ground for fundamental comparisons between theory and experiment. Both these Argonne atomic programs continue to test relativistic and quantum-electrodynamic (QED) Atomic applications provide the simplest and best-understood relativistic many-body problems. Results in such an area are important as guides to the problems of more complex molecular, solid-state and high-energy systems.

Collisions of fast heavy particles are an integral part of this atomic-structure program. Hence, some of our work involves developing a better understanding of the various collision processes. This includes some collision studies using the ATLAS ion beams: coherent excitation and ionization processes are studied in several different experiments, using rare gas, crystalline and molecular jet targets. The measurements at the Dynamitron involving measurements of molecular-ion structures have a strong component in improving our understanding of collisions of molecular and atomic heavy ions with thin solid targets.

We continue close collaborations with atomic physicists from other institutions, especially those performing calculations of few-electron systems. The experimentalists (A. E. Livingston, S. Lundeen, and C. Tanner) and the theorists (J. R. Sapirstein and W. R. Johnson) of the Notre Dame group continue to be helpful for our ATLAS-based and BLASE-based programs. Our measurements on lifetimes and wavelengths in one- and two-electron systems are primarily high-precision tests of calculation techniques of relativistic Hamiltonians in highly-charged ions. Some of the work is part of collaborations with Notre Dame; Toledo, Grenoble, France, Texas A&M, and NIST research groups. The work on many-electron (more than three) ion structures is done in collaboration with Bochum University, Germany, as well as Notre Dame and Toledo.

Our grazing-incidence and normal-incidence monochromators have been equipped with position-sensitive detectors to enhance the rate of data collection in spectroscopic and lifetime measurements. These detectors allow 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.

The program of Coulomb-explosion studies of small molecular-ion structures continues to use the Dynamitron accelerator. The Dynamitron was operated in 1992 until the end of September. The program will continue in the summer of 1993. Measurements of structures of some cooled light-diatomic and triatomic ions were completed in 1992. Particular emphasis was given to molecules of the type XH_2^+, which are analogous to 2-electron atoms. We utilized the Michigan State University Cyclotron to study the electronic wakes in solids produced by fast particles, utilizing HeH^+ as a test particle. Particle separations were measured using a high-precision double-foil target.

High-precision laser excitation of fast-ion beams at the BLASE facility continues, with the emphasis in 1992 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. D. A. Beck, Michigan Technological University, visited Argonne for 1 month in 1992, and continues to work on these problems using his new relativistic configuration-interaction, many-electron codes. Previous relativistic Hartree-Fock calculations sometimes differed by an order of magnitude or even in sign, whereas Beck's new calculations show agreement mostly to within 10%.

In an initial set of measurements at BLASE of the decay curve of the laser-excited resonance transition in cesium, we obtained a value for its lifetime to a precision of better than 1%. The measurement is important in comparing theory and experiment for the parity-violation contribution in cesium. The work is in collaboration with the University of Notre Dame group of C. Tanner and A. E. Livingston.

In the synchrotron radiation-based program, we made several measurements using the X-24A beam line at the Brookhaven National Synchrotron Radiation Source. We made accurate measurements of the ratio of double-to-single ionization of helium from high-energy photons in important tests of fundamental theory. Further measurements of absolute photoionization cross sections are in progress. Multi-electron excitation is being studied through a combination of the following diverse experimental techniques: X-ray absorption spectroscopy, high-resolution X-ray emission spectroscopy, low-resolution X-ray fluorescence spectroscopy, Auger electron spectroscopy, ion-trap studies, ion time-of-flight spectroscopy, and ion-photon coincidence studies.

The theoretical program continues as a series of visiting theorists, plus active collaborations through other mostly university-based theoretical groups. P. Sigmund of Odense University completed his term as an Argonne Fellow, through monthly visits in January 1991, January 1992 and January 1993. R. Lewis of the University of Michigan spent one week at Argonne in May 1992 helping us in estimates of anapole-moment effects in neutral atoms. M. Amusia, of the Joffe Institute in St. Petersburg, has been appointed Argonne Fellow for 1993. He will be at Argonne from April 1993 until April 1994, and will work primarily with our atomic group in the synchrotron-radiation-based program. Other active collaborations include W. R. Johnson and J. R. Sapirstein at Notre Dame, L. J. Curtis at Toledo, and D. A. Beck at Michigan Technical University, as mentioned above.

V. ACCELERATOR-BASED ATOMIC PHYSICS

A. ATOMIC PHYSICS AT ATLAS

The narrow energy spread of beams from ATLAS, together with the continuous energy variability and capability of operation in a deceleration mode, make it an ideal machine for the study of the atomic physics of highly-ionized atoms. The recently completed upgrade of ATLAS provides more intense beams and an increased range of ion species which further enhances the usefulness of ATLAS for atomic physics studies.

A number of outside groups have been attracted to the opportunities offered by ATLAS. Atomic structure studies are being pursued by a group from Notre Dame University led by A. E. Livingston, a group from Bochum, Germany led by E. Träbert, and a group from NIST led by R. D. Deslattes. L. Curtis at the University of Toledo, D. Church at Texas A&M University and M. Hass of the Weizman Institute have also been involved in atomic-structure experiments at ATLAS. Atomic-collision studies are carried out by a collaboration composed of physicists from Lawrence Livermore, Western Michigan University, and LBL. Argonne scientists collaborate with all of these outside groups.

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 spectroscopy programs at ATLAS are aimed at studying the atomic structure 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 with Notre Dame utilizes ultraviolet spectroscopy to study transitions within the n = 2 shell of two- and three-electron ions. We are using X-ray spectroscopy with the NIST group to study transitions in one- and two-electron ions. With the Bochum group we are studying 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 channeled ions.

a. Forbidden Transitions in Few-Electron Ions (H. G. Berry, S. Cheng, R. W. Dunford, D. S. Gemmell, E. P. Kanter, C. Kurtz, B. J. Zabransky, L. J. Curtis,* A. E. Livingston†)

Work on the measurement of the lifetime of the 1s2s $^1S_0$ level in helium-like bromine was completed in the past year. This level is forbidden to decay to the $1s^2\ ^1S_0$ ground state by single-photon emission due to the requirement that angular momentum be conserved in the decay. The transition takes place by the emission of two photons. Drake 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, we measured the lifetime of the 1s2s $^1S_0$ 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 of the relativistic corrections, we did an experiment on helium-like Br, where the relativistic corrections are larger. In the past year the data analysis for this experiment has been completed and we have obtained a result with an uncertainty of 0.8% which makes it the most precise test of the relativistic corrections to a two-photon decay rate.

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In the experiment, a beam of bromine ions was prepared in the 33^+ charge state and directed to a thin carbon target which excited some of the ions to the 2^1S_0 level. The decay radiation coming from the beam downbeam of the target (12-μg/cm^2 carbon) is observed with three Si(Li) detectors. The two-photon coincidence rate from this array was measured as a function of foil-detector distance in order to determine the lifetime. The requirement of a coincidence with the proper sum energy provides a powerful signature to select the helium-like two-photon decay mode, and this gives a strong suppression of transitions from two-photon decay of hydrogen-like bromine and from background (see Fig. V-1).

We also completed a measurement of the lifetime of the $2\,^2S_{1/2}$ state in one-electron krypton and the first direct determination of the branching ratio for the M1 decay of this state. This work used a similar technique but was carried out at the Cyclotron Laboratory at Michigan State University. This facility provided higher energy beams in order to obtain the fully-stripped krypton ions needed for this experiment. Our results provide a sensitive test of the relativistic corrections to the decay rate. The lifetime measurement yields 36.8(1.4) ps and the branching ratio was found to be 0.356(15) both in good agreement with the theoretical values of 37.008 ps and 0.3643, respectively. From these measurements we also deduce the corresponding magnetic dipole decay rate $A_{M1} = 9.68(55) \times 10^9\ s^{-1}$ and the two-photon decay rate $A_{2E1} = 1.750(78) \times 10^{10}\ S^{-1}$.

ANL-P-20,809

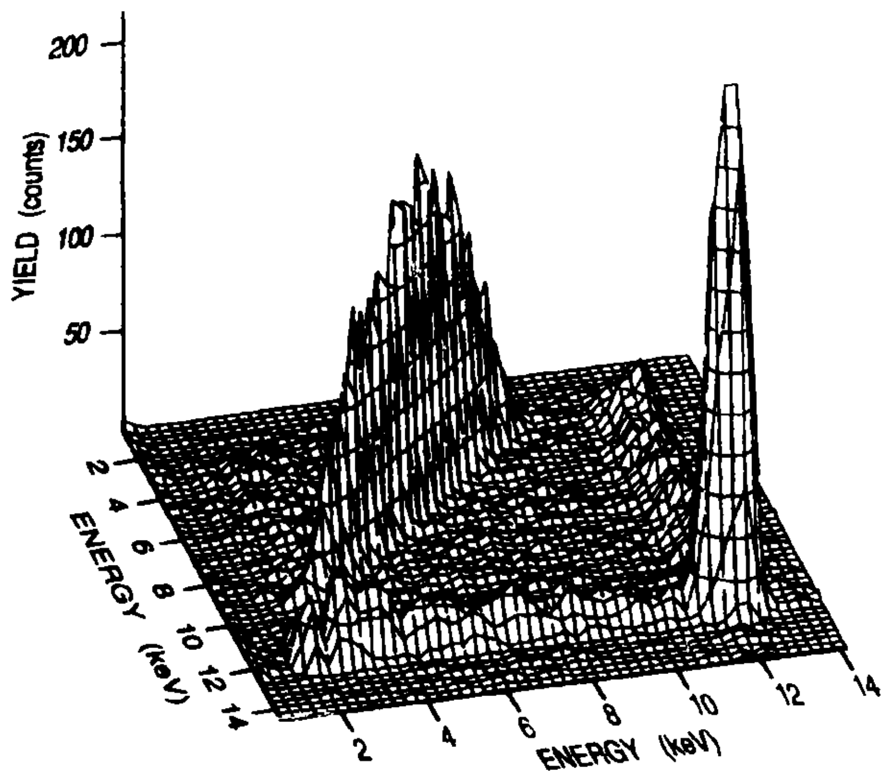

Fig. V-1. The correlation of photon energies for coincidences between detector 1 and detector 2 in the bromine experiment. The summed energies if the diagonal line can clearly be used to separate the data needed for the accurate lifetime measurement.

b. **Measurement of Transition Energies in Li-Like and He-Like Calcium**
(H. G. Berry, S. Cheng, R. W. Dunford, D. S. Gemmell, E. P. Kanter, C. Kurtz, J. Suleiman, B. J. Zabransky, R. D. Deslattes*, P. Indelicato*)

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. An important aspect of this work is the use of the accel/decel technique 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 so clean, symmetrical spectral lines, uncontaminated by lines from multielectron pickup, are obtained.

In the coming year we hope to obtain high precision measurements of the 2p-2s transition energy in helium-like Ca^{18+}. Preliminary data were obtained earlier at ATLAS. 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 also 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. Analysis of these data has been completed and provides precision comparisons of experimental and theoretical transition energies and insight into collision mechanisms involving simultaneous electron pickup and excitation.

*National Institute of Standards and Technology

c. **Precision Spectroscopy of the 2s-2p Fine Structure Transitions in Helium-like Ar^{16+} and Ni^{26+}** (H. G. Berry, R. W. Dunford, D. S. Gemmell, E. P. Kanter, C. Kurtz, B. J. Zabransky, A. E. Livingston*, F. G. Serpa*, K. Kukla*)

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: at intermediate Z, 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 energies in helium-like argon and nickel. These measurements, coupled with our earlier measurement 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 of the helium-like spectra done by G. W. F. 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 (see Fig. V-2). In addition, recent calculations by Johnson and Sapirstein have also indicated a discrepancy with the Drake calculations.

*University of Notre Dame

We have recently completed our first run of the experiment in helium-like argon. A number of improvements were made prior to this run to enhance our sensitivity. One of the improvements was the development of a position-sensitive detector for the monochromator. By replacing the exit slits and channeltron with a microchannel plate detector and a resistive anode, we have greatly improved the detection efficiency of the system. Also we have been able to reduce the background in the spectrum by suppressing ion-beam-related signals. This was achieved by shielding the beam dump

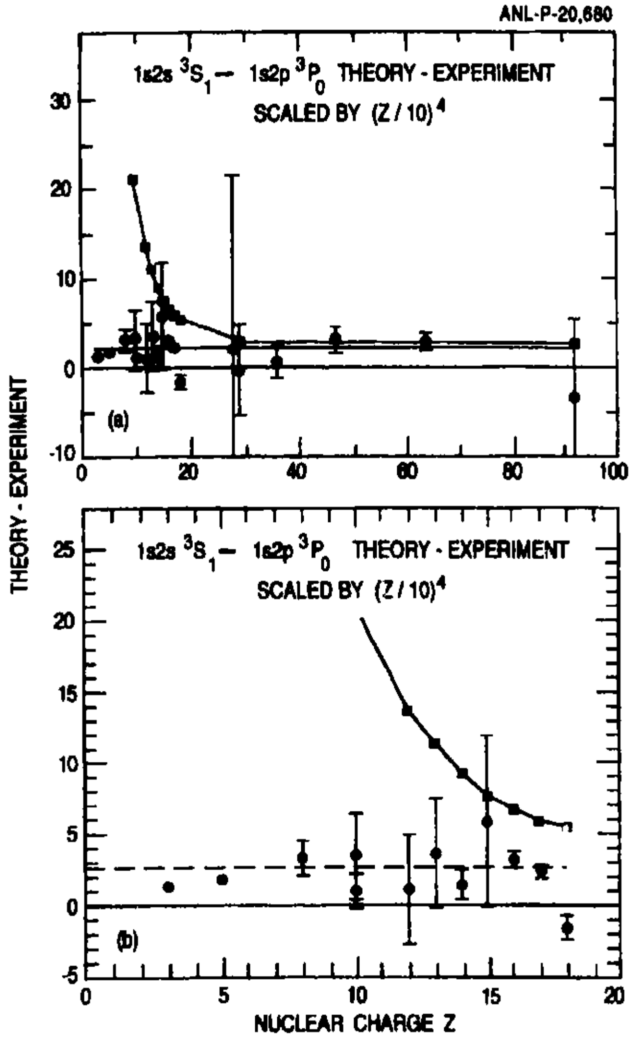

Fig. V-2. Comparison of theory (Drake) and experiment for the 1s2s $^3S_1$ -1s2p $^3P_0$ transitions: the differences in cm^{-1} between theory and experiment are scaled by $(Z/10)^4$. The circles are experimental values; solid squares - theory of Indelicato. (b) Enlarged view of nuclear charges $3<Z<19$. The horizontal line at $2.3 \times (Z/10)^4$ in (a) and (b) is our estimated correction. Argonne/ Notre Dame measurements are those at Z =3, 5, 15-17. Our proposed new Z = 18 measurement will test the accuracy of the previous Z = 18 measurement.

and by discriminating the time of 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; thus, by cutting out all events which do not come at the proper time relative to the beam, the background was greatly reduced.

d. Search for Anapole Moments (H. G. Berry, R. W. Dunford, E. P. Kanter, L. Young, D. Lee,* R. Kaye,† and S. Collins‡)

The anapole moment is a toroidal dipole moment of current, which violates time reversal but not parity reversal invariance. Thus such a moment can be produced in an atom through the parity-violating part of the electroweak interaction. No anapole moment has ever been conclusively observed. We have begun a preliminary study to identify a good method for measuring such an anapole moment in atoms. We made a systematic search for and identified several sets of close-lying opposite parity levels in neutral atoms. We believe that the anapole moment effect can be enhanced over other parity-violating effects by studying such pairs of levels whose angular momentum differs by one unit.

An initial experiment was proposed to study optical rotation in a hot atomic vapor. Initial measurements may take place in cesium (no close-lying opposite parity levels). Further measurements may take place in other hot rare-earth vapors.

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*High School Student from Kenwood High School, †Undergraduate Student from Florida State University, ‡Undergraduate Student from Lawrence College

B. COULOMB EXPLOSION IMAGING EXPERIMENTS AT THE DYNAMITRON

The Coulomb-explosion program during FY 1992 concentrated on the application of CEI imaging to the study of bending vibrations in several small polyatomic molecules. In addition, as a result of some anomalies observed previously in investigations of diatomic molecular ions with ultra-thin targets, studies of bond length dependent charge changing were also carried out. Operation of the Dynamitron for these experiments was suspended in September 1992.

a. The Coulomb Explosion of HeH^+ at High Energies (M. P. Carpenter, R. W. Dunford, D. S. Gemmell, E. P. Kanter, R. V. F. Janssens, J. A. Nolen, Z. Vager, and B. J. Zabransky)

An experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. The aim of the experiment was to exploit the existence of a high-energy (35-MeV/A) HeH^+ beam to study details of the electronic "wakes" induced in solids by the passage of swift charged particles. A diatomic molecular-ion projectile undergoing a "Coulomb explosion" provides a good probe of these wake effects since the wake forces cause significant changes in the alignment of the internuclear vector joining the two separating fragments. A wake represents the collective electronic response of the solid to the passage of a fast ion. The wake "wavelength" is the distance the ionic projectile travels in one plasmon oscillation period and lies typically in the range of about 15-300 Å for ions with energies in the range of about 1-50 MeV/nucleon. Almost all Coulomb-explosion experiments thus far performed with solid targets have been sensitive to the wake force over distances of only about 1 Å (the fragments' internuclear separation during passage through the solid). The experiment at MSU used a unique double-foil target arrangement with inter-foil separations variable (down to zero) in the micron range with a view to extending these studies out to distances of several wake wavelengths. In addition, Coulomb-explosion data were recorded for a variety of single-foil targets. Analysis of our initial measurements on the proton fragments emerging in the beam direction from these foil-induced dissociations revealed energy shifts that were only about 70-80% of the values expected. Also, no oscillatory effects were observed in the data taken with double-foil targets even though such effects were predicted on the basis of computer simulations. Before drawing conclusions from these results we need to establish whether or not they arise from any possible small misalignment in our experimental apparatus. A measurement to check this is now planned. With the recent completion of the ECR positive-ion injector at ATLAS, it becomes feasible to accelerate molecular ions such as HeH^+ and H_2^+ to energies of about 10 MeV/A and we now plan to pursue this option in studying these effects further.

b. <u>**Positron Production in Heavy-Ion Collisions**</u> (R. W. Dunford and the APEX collaboration)

In the past year preparations have continued for the positron experiment at ATLAS. The first uranium beams have been delivered to the apparatus in preparation for the first runs in early 1993. We continue our involvement in the ATLAS Positron EXperiment (APEX) which is designed to investigate the unexplained electron-positron coincidence peaks which have been observed in collisions of very heavy ions (e.g., U + Th, U + U, U + Ta) at the UNILAC accelerator at GSI, Darmstadt. These peaks are still not understood and they are among the most puzzling phenomena in physics at the present time. The explanation may require an understanding of the atomic physics associated with the highly-charged combined nucleus formed in the collision.

c. <u>**Cooling of Bending Modes in Polyatomic Molecules**</u> (T. Graber,* E. P. Kanter, Z. Vager, B. J. Zabransky, and D. Zajf man)

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, 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 and demonstrated with extensive studies of several diatomic molecular ions. In particular, we had succeeded previously in vibrationally cooling He_2^+, H_2^+, and N_2^+ as evidenced by the bond length distributions measured by Coulomb-explosion techniques.

As a part of our effort to study bending vibrations in polyatomic molecules, further refinements to the source were necessitated. Principal modifications included more complete electrostatic shielding, a longer expansion region, and installation of a skimmer. With these refinements, we have now succeeded in vibrationally cooling a broad class of molecules. Among those studied were: CH_n^+ (n = 2-5), NH_n^+ (n = 2-4), H_nO^+ (n = 2,3), and $C_2H_n^+$ (n = 1-3). In each case, we were able to demonstrate cooling of the various bending modes observed in each.

d. <u>**Bending Vibrations in Dihydride Molecular Ions**</u> (T. Graber,* E. P. Kanter, Z. Vager, B. J. Zabransky, and D. Zajfman)

The series of light di-hydride molecular ions (CH_2^+, NH_2^+, and H_2O^+) provide an interesting case of Renner-Teller molecules with very different potential surfaces. Each is

*Resident Graduate Student from University of Illinois.

thought to possess equilibrium geometries with barriers, of differing heights, to linearity. Whereas H_2O^+ has been extensively studied and known to exhibit a large barrier to linearity, the other two have been more problematic. Because the barriers in those cases are thought to be substantially smaller, spectroscopic results have not been as successful in describing these "quasi-linear" molecules.

In order to clarify this problem, we have during the past year applied the Coulomb-Explosion Imaging (CEI) technique to beams of these molecules prepared with variable vibrational temperatures. By observing the change in the bend-angle distributions as the molecules are cooled we have succeeded in characterizing the ground-state geometries, and potential barriers, of each of these molecules. Our findings for CH_2^+ have demonstrated conclusively that the electronic ground-state potential of this molecule has a C_{2v} minimum and that the zero-point energy lies below the linear barrier. In contrast, it appears at present that the barrier in NH_2^+ is below the zero-point energy. Further work in this case is required to prove that the molecule has been sufficiently cooled to be certain of this preliminary conclusion (see Fig. V-3).

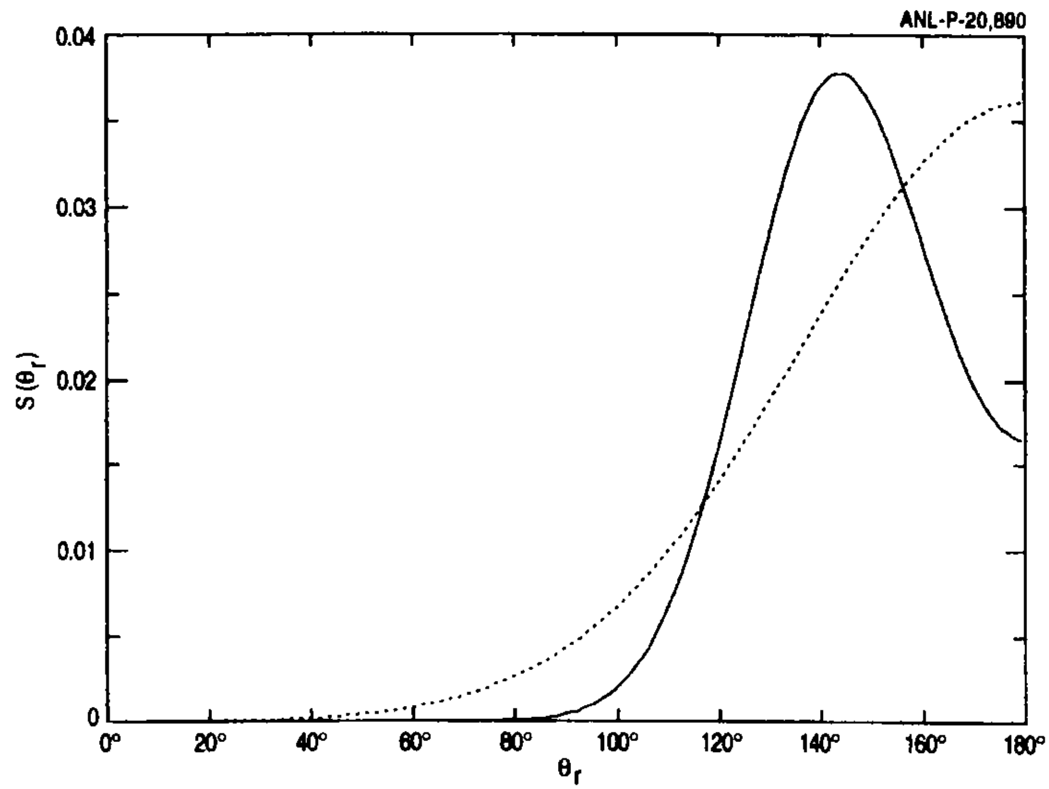

Fig. V-3. Experimental H-C-H bond-angle distributions measured for CH_2^+ under different source conditions. The solid curve shows the experimental distribution for the coldest ensemble of molecules measured, while the dashed curve shows the same distribution for a "hot" ensemble.

e. Experimental Determination of an Isomerization Reaction Path in CH_4^+
(T. Graber,* E. P. Kanter, Z. Vager, B. J. Zabransky, and D. Zajfman)

As a highly fluxional Jahn-Teller distorted system, the methane cation has for many years proved an interesting challenge to both experimental and theoretical techniques. Our previous Coulomb-explosion studies of CH_4^+ were necessarily very limited in scope because of the hot ensembles of molecules employed. During the past year however, we have been able to study vibrationally cold ensembles of molecules and from such data extract direct information on the intramolecular isomerization path.

By measuring the complete 9-dimensional nuclear probability density for this molecule, we have been able to trace the isomerization paths between the various C_{2v} conformations. This particular isomerization has been studied theoretically, and those predictions are in excellent agreement with our experiment. Specifically, we find a non-least-action pathway through the transition state as predicted. Further analysis is underway to map these data to configuration space which will enable us to quantify the angle changes (see Fig. V-4). These data hint at a powerful new tool to study reaction dynamics in polyatomic systems.

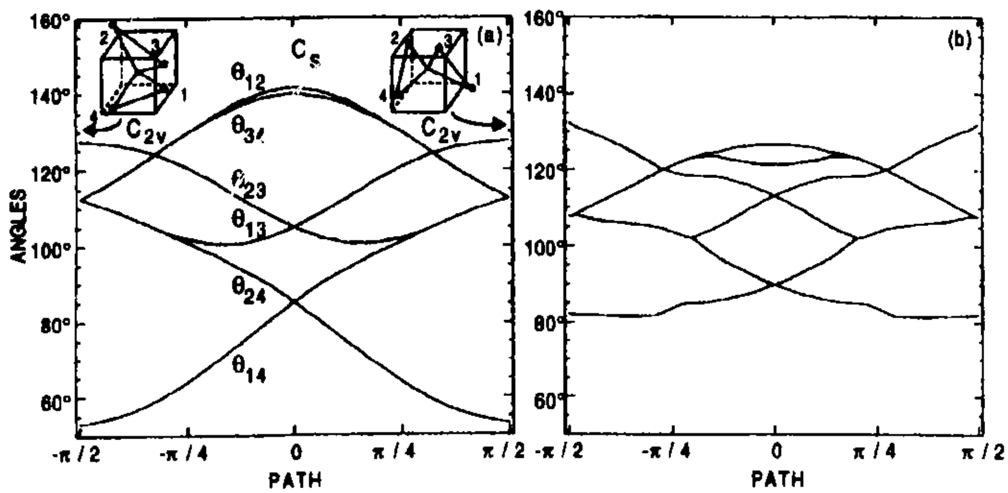

Fig. V-4. H-C-H angles along the reaction path between two equivalent conformations of CH_4^+. The abscissa represents a phase angle along the path between these conformations. (a) Theoretical reaction path from the ab initio potential surface. (b) Experimental reaction path deduced from Coulomb-explosion data.

f. Bond-Length Dependence of Charge Changing (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 separate unambiguously "Coulomb-explosion" effects from those of structure. This has proved extremely important in ascertaining the role of various collisional effects which had been hinted at previously by experiments, but have been extremely difficult to disentangle. By carrying out measurements on vibrationally cold helium dimer ions with ultrathin targets and comparatively high energies, we have been able to observe a bond-length dependence in the final charge-state distributions of He ions. Such measurements provide an interesting probe of electron capture with nonspherically-symmetric systems.

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C. FAST-ION-BEAM/LASER STUDIES AT BLASE

During this year we have completed high resolution laser measurements of the hyperfine structures of several singly-charged heavy ions, using our fast-ion-beam/collinear-laser fluorescence and rf double-resonance techniques. Detailed comparisons with new configuration interaction relativistic many-body calculations of D. A. Beck (Michigan Technological University) have been very fruitful. Our first, but very precise fast-beam/laser-lifetime measurement was achieved in neutral cesium (in collaboration with C. Tanner and A. E. Livingston, Notre Dame) at BLASE. Further measurements will be made in cesium and some new measurements in lithium are proposed to clarify the reason for a long-standing discrepancy between theory and experiment.

a. Laser-RF Double-Resonance Measurements of the Hyperfine Structure in Ti II (C. A. Kurtz, L. Young, N. Berrah-Mansour,* D. A. Beck,† and D. Datta†)

As an extension of the previous studies of transition metal ion hyperfine structures (hfs), we have progressed from systems having two valence electrons to those having three valence electrons. The first "three-electron" atom studied was Ti II. These studies are motivated by the goal of being able to predict hfs from first principles in these complex systems, and spurred by the recent theoretical achievements of D. A. Beck in the *ab initio* calculation of hfs in the two valence electron atoms. The methodology is to determine systematically which many-body interactions are important in levels where the independent particle approach fails dramatically. This is accomplished using a perturbation-theory directed configuration interaction approach. The knowledge gained from these "difficult" cases can then be applied to predict hfs in other levels. In addition, the combination of hfs and oscillator strengths are very stringent tests of the wavefunctions obtained, since the hfs weights the portion of the wavefunction near the nucleus $<r^3>$ while the oscillator strengths weight the portion far from the nucleus $<r>$.

In ^{49}Ti II, we measured the hyperfine structures of six metastable levels arising from the $3d^24s$ and $3d^3$ configurations using the laser-rf double resonance method in a collinear laser-ion beam geometry. The hfs constants A and B were determined to be about 4 and 43 kHz, respectively. Less precise results were obtained for the $^2P_{1/2}$ level of the $3d^3$ configuration and for five upper levels in the $3d^24p$ configuration using optical spectra only. The results were compared with the Hartree-Fock calculations. Good agreement is obtained only in some cases. Substantial corrections due to many-body interactions and relativistic effects are required in other cases.

A paper reporting these results has been published. In addition, many-body calculations are planned to resolve discrepancies between the Hartree-Fock and experimental values.

*University of Western Michigan, †Michigan Technological University

b. Hyperfine Structure Studies of Zr II (L. Young, C. A. Kurtz, D. A. Beck,* and D. Datta*)

The second effective three-electron atom studied was the homologous ion ^{91}Zr II. It was chosen both to test the magnitude of relativistic contributions compared to the Ti II case, and as a testing ground for the newly-developed relativistic computation algorithms. Two levels

*University of Western Michigan, †Michigan Technological University were of special interest as the analogous levels in Ti II showed very large, and as yet unexplained, deviations from the Hartree-Fock (non-relativistic, independent particle) values.

Experimentally, hyperfine structures in 11 levels arising from the metastable $4d^3$ and $4d^25s$ configurations were measured using the laser-rf double-resonance method. The hfs A and B constants were measured to 4 and 11 kHz precision, respectively. Less precise values for hfs constants were derived from optical spectra for 9 upper levels in the $4d^2$ configuration.

Theoretically, the many-body problem was treated with a relativistic configuration interaction approach. Since one is starting with relativistic wavefunctions, all levels with a given J must be calculated simultaneously. Two Js were selected for the initial study, J = 3/2 and J = 1/2.

These include the levels which were so discrepant with Hartree-Fock values in Ti II, i.e. nd^3, $^2P_{3/2}$ and $^2P_{1/2}$ The calculations start with a zeroth-order wavefunction which is a multiconfigurational Dirac-Fock (MCDF) solution. Many-body effects are then included by allowing configurationally single and double excitations from the zeroth-order function. By adding such excitations in a systematic fashion, the various many-body effects can be distinguished from one another. The calculated wavefunctions should predict simultaneously the measured level energy, hfs A and B constants. For the J = 3/2 levels, the average energy discrepancy for the ten lowest roots was ≈ 700 cm^{-1} and the average discrepancy with the three measured A-values was less than 10%. This represents a remarkable improvement over the independent particle Dirac-Fock values for the A-values, which were of the *wrong sign* in two out of three cases. It is particularly gratifying to note that the three measured J = 3/2 levels were those exhibiting the largest many-body effects, i.e., whose A-values changed the most between the MCDF and the many-body result, and that the theory predicted all three quite well. A paper describing these results is being submitted for publication.

c. **Laser-RF Double-Resonance Studies of Hyperfine Structure in V II** (L. Young, C. A. Kurtz, S. Hasegawa,* and G. Matous†)

As a logical extension on hfs studies in transition-metal ions, we next studied a system with four valence electrons, V II. Using the laser-rf double-resonance method, we measured the hfs in 4 levels arising from the $3d^4$ and $3d^34s$ configurations. Because of the very large nuclear magnetic moment in ^{51}V, it was necessary to frequency double the output of the radio-frequency synthesizer (<2.4 GHz) in order to reach the resonances. Even so, some resonances were not within reach (<4.8 GHz), and hfs of these states was only determined through optical spectra. Since the doubled output is not pure, i.e. contains both fundamental and second harmonic, it was possible to observe two-photon rf transitions. Of the four levels studied using the laser-rf double resonance method, two arose from the $3d^3$ 4s and two from the $3d^4$ configuration. In addition, hfs from six other levels was measured using optical spectroscopy. Typical precisions for the rf measurements were 5 kHz and 10 kHz for A and B, respectively. Many-body calculations by D. A. Beck are planned in the near future.

*University of Tokyo †University of Western Michigan

d. **Hyperfine Structure Studies in Nb II** (L. Young, C. A. Kurtz, S. Hasegawa,* D. A. Beck†)

The next system studied with four valence electrons was Nb II. Similar to ^{51}V, the ^{91}Nb isotope has a large nuclear magnetic moment, 6.167 μ_N, and thus required frequency doubling of the rf output. In addition, some of the optical pumping transitions were very weak, with oscillator strengths of 10^{-4}. This motivated us to install a photodiode detector near a beam profile monitor (rotating wire) in order to ensure optimum laser-ion beam overlap in the optical pumping region. We measured the hfs of the $^3F_{2,3,4}$ states in the $4d^4$ configuration using the laser-rf double-resonance technique. Lower precision optical measurements have been made on the $4d^35p$ $^3D_{1,2}°$ levels. The $3d^4$ $^3F_{3,4}$ levels show evidence of second-order hyperfine structure. Preliminary Dirac-Fock calculations on the even-parity levels show excellent agreement for the J = 3 level but are several hundred percent discrepant with the J = 2 and 4 levels. Many-body calculations are underway in order to resolve the discrepancy with the independent particle picture.

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e. **Precision Lifetime Measurements in Cesium** (H. G. Berry, L. Young, C. A. Kurtz, C. E. Tanner,* A. E. Livingston,*, R. J. Rafac,*, F. G. Serpa,* and K. W. Kukla*)

A new program of precision lifetime measurements was initiated at BLASE in collaboration with a group from the University of Notre Dame. The technique used was the "beam-laser" method, in which the fast beam ($\beta \approx .01$) is selectively excited using a perpendicularly crossed laser beam, and the decay of the fluorescence is monitored as a function of the distance downstream from the excitation point. The initial experiment was done on the 6p $^2P_{3/2}$ state in Cs because of the recent experiments in atomic parity nonconservation in this atom. The interpretation of these experiments in terms of fundamental weak interaction coupling constants requires accurate atomic structure calculations. This measurement of the oscillator strength provides a direct test of the recent relativistic many-body calculations of the 6S-6P transition matrix element.

The lifetime was measured by using a diode laser to excite a fast cesium atomic beam and detecting the decay of the fluorescence downstream from the excitation point using a movable 6 mm fiber-optic bundle. A second fiber-optic bundle for normalization was placed directly behind the excitation point and upstream of the movable detector. Decay curves were measured by accumulating photon count signals at 28 equally-spaced positions along the fast beam over a distance of 4 decay lengths. Background corrections were measured by making sequential decay-curve measurements with the laser tuned off resonance. The velocity of the beam was measured by collinear excitation of the fast atomic beam by a second diode laser, the frequency of which was monitored on a wavemeter. A total of 26 decay measurements were taken, and the standard deviation of the mean lifetime was 0.04% for all the decays. The precision of the final result, however, is limited by systematic uncertainties to 0.9%.
A paper reporting these results was published. A second generation experiment is currently underway to measure the 6p $^2P_{1/2}$ lifetime in addition to that of the 6p $^2P_{3/2}$ state more accurately.

*University of Notre Dame

VI. SYNCHROTRON RADIATION BASED ATOMIC PHYSICS

A research program in atomic, molecular and optical physics with X-rays has been initiated to complement the highly successful program of accelerator-based atomic-physics research within the Division. This program is also expected to be a key component of the Basic Energy Sciences Synchrotron Research Center, which will encompass a wide variety of research in the physical sciences.

In anticipation of constructing and operating the world's first synchrotron-radiation experimental station at a third-generation synchrotron X-ray source to be dedicated to AMO physics, the group has assumed partnership with the Quantum Metrology Division of NIST as part of the Participating Research Team for NSLS beam line X-24A. This agreement will provide the group priority access to this state-of-the-art dedicated facility for research in AMO physics with synchrotron radiation.

The goals of this program are two-fold. First, it is intended to exploit the unique characteristics of X-rays for studies of atomic and molecular structure and dynamics, especially the inner shells. Photons at X-ray energies are anticipated to be particularly useful for studies of correlation, relativity, and quantum electrodynamics (QED). Second, the relative simplicity of atoms and simple molecules provides an ideal testing ground for studies of the basic interactions of X-rays with matter, for comparison to similar phenomena in more complex systems, such as condensed matter or macro molecules. Advances towards these goals are expected to occur concurrently with advances in X-ray optical physics, especially those made possible through the availability of advanced synchrotron-radiation sources.

Successful prosecution of this program depends critically on the availability of funding for three classes of facilities. In order of decreasing scale they are as follows: First, the special-purpose beam-line apparatus for AMO physics at the third generation synchrotron-radiation sources must be designed and constructed. Second, full advantage of existing second-generation synchrotron-radiation facilities, especially those few dedicated to AMO Physics with X-rays, must be exploited. Third, an in-house infrastructure of laboratory equipment must be available for testing and development of new equipment, techniques, and in some cases, for execution of suitable experiments.

Multi-electron excitation is being studied through a combination of the following diverse experimental techniques: X-ray absorption spectroscopy, high-resolution X-ray emission spectroscopy, low-resolution X-ray fluorescence spectroscopy, Auger electron spectroscopy, ion-trap studies, ion time-of-flight spectroscopy, and ion-photon coincidence studies. This broad-based experimental program is being accomplished through the technical expertise available within the group, and partially through external collaboration.

a. <u>X-Ray Absorption Spectroscopy of Inner-Shell Double Photoexcitation</u>

(Y. Azuma, H. G. Berry, P. L. Cowan, D. S. Gemmell, T. LeBrun, T. Sekioka,* J. Suleiman,† and M. Westerlind‡)

Our previous measurements of Kr deep inner-shell double photoexcitation at the Stanford Synchrotron Radiation Lab SPEAR storage ring, in collaboration with the University of Oregon group, was partially successful, but left a number of open questions. This year we have initiated a series of independent measurements at the NSLS X-24A beam line, utilizing a new set of double-ion chambers. Total photoexcitation cross sections were

*Himeji Institute of Technology, †Resident Graduate Student, University of Illinois, ‡University of Tennessee studied both via transmission measurements, and through enhanced yield due to presence of sample gas in the ion-chamber mixture. Absorption spectra of Ar show the KM and KL [1s2p] double photoexcitation features with much improved S/N ratio as well as better resolution compared with previous data. The goal is the observation of relativistic and QED corrections to the fine structure of these inner-shell double-hole states. These measurements are expected to aid future studies of multiple excitation via secondary emission spectroscopy. Also, preparations for absorption measurements on alkali metals and other more refractory elements utilizing a heat pipe are in progress.

b. **Photoion Charge-State Yield Measurement near Ar-K Threshold** (Y. Azuma, H. G. Berry, P. L. Cowan, D. S. Gemmell, T. LeBrun, R. Miller,* and N. Berrah†)

The charge-state yield following K-shell photoexcitation, in the vicinity of the edge region was measured at the NSLS X-24A beam line, utilizing a new time-of-flight (TOF) analyzer constructed by T. LeBrun. The development of the TOF analyzer has continued and a detector response of 200 psec was achieved. This spectrometer, when used in conjunction with single-bunch operations of the NSLS X-ray ring, enables one to determine ion-charge-state distributions that result from X-ray inner-shell excitations.

This new apparatus has been used alone in two types of studies, and has also been used in conjunction with photon coincidence as discussed in a separate section. The two studies in which the ToF spectrometer was the only secondary detector were studies of near-threshold inner-shell excitation and studies of ion-charge distributions due to multiple excitation. The dependence of charge-state distribution near threshold reveals the effect of shake-off, recapture, and post-collision interaction (PCI). The ion-charge-state distribution is produced in the vicinity of multi-excitation features in X-ray absorption spectra and is expected to provide additional information for assignment of these various features.

c. **Fluorescence Yield Measurements and Photon-Ion Coincidence Studies near Ar-K Threshold** (Y. Azuma, H. G. Berry, P. L. Cowan, D. S. Gemmell, T. LeBrun, R. Miller,* and N. Berrah†)

The excitation energy dependence of the fluorescence yield of Ar-Kα and Ar-Kβ emission lines were measured with a low-resolution Si(Li) detector. These measurements also address questions concerning the dynamics of the atom following inner-shell excitation. Evidence from high-resolution X-ray emission spectroscopy and other studies developed circumstantial evidence that the fluorescent yield for sub-threshold K-excitation might be significantly smaller than the above threshold. Our studies show there is a small, but significant difference between the fluorescent yield of Kα and Kβ emission. This difference is believed to be due to interaction spectator electrons present for sub-threshold excitation.

Preliminary photon-ion coincidence measurements combining the time-of-flight analyzer and Si(Li) detector have also been done for the first time, in an effort toward more complete measurement of the PCI in the near-threshold region. The cases of ions in coincidence with Kα or Kβ fluorescence are of particular interest. In the former case (Kα) the atom or ion is left with a [2p] hole, which will almost always decay via the emission of an Auger electron, while in the latter case (Kβ) no subsequent Auger decay can occur. This makes this comparison particularly sensitive to the interaction of the Auger electron with bound spectator electrons or near-threshold photo-electrons.

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d. X-Ray Resonant Raman Spectroscopy (XRRS) of Xenon (P. L. Cowan, T. LeBrun, R. D. Deslattes,* S.H. Southworth,* and J. Levin*)

Recently X-ray resonant Raman scattering has attracted great interest as a high-resolution X-ray spectral probe of the electronic structure of matter. This interest stems from the observation that, unlike XAS and conventional XES, XRRS is not restricted in energy resolution by inner-shell-hole lifetime broadening. Furthermore, previous measurements of polarization and angular anisotropic effects have proved the potential value for studies of both symmetries of electronic states and atomic structure of molecules.

The continuation of such studies to the case of L-edge excitation of xenon gas has several motivations. First, this case is interesting for technical reasons, since the lifetime broadening (roughly 3 eV) is significantly greater than the typical instrumental resolution in this energy range. Second, the host of fluorescence decay channels offer a number of possibilities for dramatic polarization effects in this non-molecular system. Third, the extension of previous studies to L-shell excitation anticipates a number of potential applications to condensed-matter studies.

Preliminary results from XRRS from the Xe-L region has already demonstrated that some of the more simplistic claims made for XRRS by other researchers are somewhat naive. However, equipment deficiencies forced the temporary suspension of these studies before some of the more interesting polarization and spectral-narrowing phenomena could be fully investigated. It is anticipated that this work will resume in the coming year.

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*National Institute of Standards & Technology

e. Planning for Basic Energy Sciences Synchrotron Radiation Center and other Facilities at Advanced Photon Source (P. L. Cowan, G. Knapp*, and P. Montano*)

During the past year a detailed conceptual design for the proposed BESSRC beam lines and experimental stations, including the atomic-physics station, was constructed and submitted to the APS for evaluation. One key element of this study was a detailed analysis of the undulator-insertion device which will serve the atomic-physics station. The characteristics of this source strongly influence design decisions concerning beam-line optics and performance. As a result of this analysis a modification to the design of the standard APS undulator magnetic lattice has been proposed for the BESSRC beam line, and is currently under consideration by the APS staff.

In addition to the undulator-source studies, detailed consideration of the performance of X-ray mirrors, monochromators and timing shutters was conducted, with special emphasis on the anticipated effects of the high radiated power loads expected for the APS insertion devices.

In addition to planning activities for the BESSRC beam lines, P. Montano and P. L. Cowan were invited to participate in the newly formed Synchrotron Radiation Instrumentation Collaborative Access Team (SRI-CAT). The role of P. Montano and P. L. Cowan, along with a number of other scientific members, is primarily to provide scientific guidance to the APS staff members, who will be mainly responsible for the actual instrumentation development. This participation of scientific members will provide them with access to state-of-the-art facilities for a number of technically-demanding experiments including inelastic X-ray scattering and spectroscopic studies in the difficult 500-eV-2000-eV energy range.

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*Materials Science Division, ANL

f. Theoretical and Experimental Investigations and Developments in X-Ray Optics
(P. L. Cowan, A. Macrander,* D. Haeffner,* S. Brennan,† M. Bedzyk,‡ and J. Woicik§)

Theoretical and experimental studies of a variety of problems in X-ray optical physics continued. A joint theoretical analysis of the so-called inclined-crystal monochromator, which is the basis of the proposed APS X-ray monochromator for use on undulator beam lines, was performed by A. Macrander, D. Haeffner, and P. L. Cowan. A. Macrander's and D. Haeffner's analysis was based on the real-space matrix methods developed by S. Brennan and A. Macrander, while P. L. Cowan's was based on his work on the extended Ewald-Laue theory of dynamical diffraction. The two methods were shown to reproduce each other's results when the geometry of the inclined-crystal case was properly described in the matrix formalism.

Experimental studies of the formation of X-ray standing-wave fields continued to be pursued in collaboration with J. Woicik of NIST and his co-workers. The primary outcome of these studies has been the unambiguous determination of surface structure for a variety of cases, but additional studies of novel optical arrangements including X-ray mirrors as well as crystal optics has presented new methods for the future application of this technique.

Theoretical studies of various X-ray phase-plate concepts continued in the past year. Since control of X-ray polarization is rapidly becoming an important tool for X-ray studies in AMO physics as well as in condensed-matter physics, these studies are particularly timely for the ongoing BESSRC beam-line designs. Experimental tests of such devices are anticipated in the coming year.

*Experimental Facilities Division, ANL, †Stanford Synchrotron Research Laboratory, ‡Materials Science Division, ANL, §National Institute of Standards & Technology

g. Beam-Line Improvements, and Studies of NSLS Beam Line X-24A
(Y. Azuma, H. G. Berry, P. L. Cowan, T. LeBrun, R. D. Deslattes,* S. H. Southworth,* and J. Levin*)

A variety of studies of novel synchrotron-radiation beam-line optical components were attempted in the past year. The goals of these efforts were (a) to extend the performance of NSLS beam line X-24A, which is partially supported by this group and is the first X-ray beam line dedicated to AMO physics in the US, and (b) to stay at the state-of-the-art in synchrotron-radiation beam-line technology in anticipation of the final design and construction of the BESSRC beam lines at the APS. Recent efforts at X-24A have included the successful completion of a novel high-transmission X-ray beam-position

monitor, the successful installation of a new monochromator-crystal cooling system, the successful testing and use of an InSb(111)-crystal pair and an InSb(111)/KDP(200) matched pair, studies of matched multilayer-KAP(002) and multilayer-RAP(002) crystal pairs, first test and use of a fixed-radius von Hamos sagittally-focusing monochromator crystal, and te of a low-dispersion wide-band multilayer Bragg-reflection pre-filter.

* National Institute of Standards & Technology

h. Ratio of Double-to-Single Ionization of Helium (Y. Azuma, H. G. Berry, N. Berrah-Mansour,* J. Levin,† I. A. Sellin,‡ R. D. Miller‡, D. W. Lindle,§ B. Johnson,¶ and D. H. Lee¶)

We used the NSLS X-ray ring to continue our studies of the double photoionization of helium at high-incident photon energies. In FY 1992 we extended these measurements to higher-incident photon energies, reaching an energy of 12 keV. The new measurements above 4 keV utilized a lower energy resolution than the previous measurements, and took place at beam line X8. Energy resolution was provided by a series of foil filters. The results are consistent with the previous measurements, and indicate a limiting value for the ratio of double-to-single photoionization at the highest energies of 1.5%. This is in agreement with several calculations which were published in 1992 (Dalgarno) or will be published (Hino).

In new work, we hope to measure the absolute photoionization cross section at these high energies. The measurements are needed to check new predictions for the contributions from the Compton effect with production of singly- and doubly-charged helium ions. Preliminary results are shown in Fig. V-1, where we see clearly our sensitivity to the very small Compton scattering cross section above 5-keV photon energy.

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*Western Michigan University, †National Institute of Standards & Technology, ‡University of Tennessee, §University of Nevada, ¶Brookhaven National Laboratory

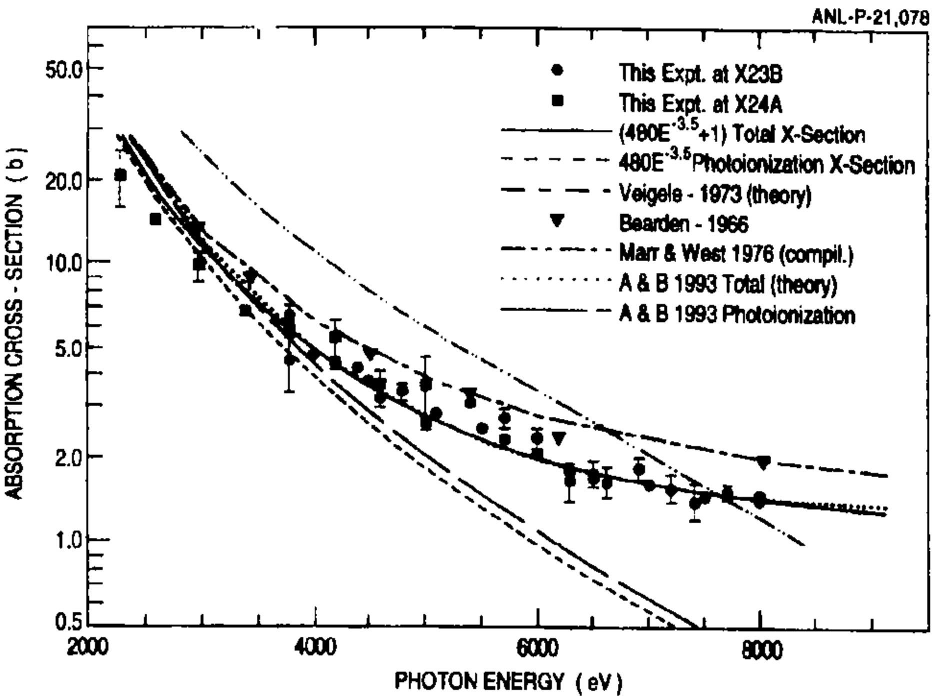

Figure VI-1. The helium photoabsorption cross section up to 8 keV. Our data points (circles and squares) are compared with several calculations including and excluding the Compton cross section.

i. **Ar-K Auger Satellite and Photoelectron Satellite Measurements** (Y. Azuma, P. L. Cowan, T. LeBrun, M. Macdonalds,* and S. Southworth*)

High-resolution electron spectrometry utilizing a clindrical mirror analyzer was pursued at the NSLS X-24A beam line, in collaboration with the NIST group. Satellite lines of the Auger electrons and photoelectrons due to shake offs and shake ups were measured. Also, data on line-shape distortion due to PCI were obtained. Analysis of the initial data is underway, and further experiments are expected.

*National Institute of Standards & Technology

j. **Auger Resonant Raman Measurements** (Y. Azuma, P. L. Cowan, T. LeBrun, M. Macdonalds,* and S. Southworth*)

The Auger resonant Raman effect on Ar was studied by measuring the K-L2L3 (1D2) Auger diagram line as well as its 4p and 5p spectator satellites with the CMA. The incident photon energy was scanned across the resonant excitations and the near-K-threshold region. The linear dispersion as well as the narrowing of 4p and 5p spectator satellites characteristic of the resonant Raman effect were observed. The diagram line showed a more complicated behavior due to the additional effect from Post Collision International. Further experimental studies are anticipated before publication.

*National Institute of Standards & Technology

k. **Angle-Resolved Photoelectron Spectrometry of Atomic Nitrogen** (Y. Azuma, C. D. Caldwell,* S. J. Schaphorst,† and S. Whitfield*)

Collaborative experiments with C. D. Caldwell and M. O. Krause were carried out at the Synchrotron Radiation Center (SRC) in Stoughton, Wisconsin. Angle-resolved photoelectron spectrometry of open-shell atoms produced by the dissociation of molecules by microwave discharge was pursued. In particular, the photoionization cross section of atomic nitrogen 2s2p3np autoionizing states and the b parameter over the 2s - 3p and 4 resonances were measured and found to compare favorablywith multi-configuration Hartree-Fock (MCHF) calculations.

*University of Central Florida, †National Institute of Standards & Technology

VII. THEORETICAL ATOMIC PHYSICS

a. Scaling Laws Governing the Multiple Scattering of Diatomic Molecules under Coulomb Explosion (P. Sigmund*)

The trajectories of fast molecules during and after penetration through foils are governed by Coulomb explosion and distorted by multiple scattering and other penetration phenomena. A scattering event may cause the energy available for Coulomb explosion to increase or decrease, and angular momentum may be transferred to the molecule. Because of continuing Coulomb explosion inside and outside the target foil, the transmission pattern recorded at a detector far away from the target is not just a linear superposition of Coulomb explosion and multiple scattering.

The velocity distribution of an initially monochromatic and well-collimated, but randomly oriented beam of molecular ions is governed by a generalization of the standard Bothe-Landau integral that governs the multiple scattering of atomic ions. Emphasis has been laid on the distribution in relative velocity and, in particular, relative energy. The statistical distributions governing the longitudinal motion (i.e., the relative motion along the molecular axis) and the rotational motion can be scaled into standard multiple-scattering distributions of atomic ions. The two scaling laws are very different. For thin target foils, the significance of rotational energy transfer is enhanced by an order of magnitude compared to switched-off Coulomb explosion. A distribution for the total relative energy, (i.e., longitudinal plus rotational motion) has also been found, but its scaling behavior is more complex. Explicit examples given for all three distributions refer to power-law scattering.

As a first approximation, scattering events undergone by the two atoms in the molecule were assumed uncorrelated. A separate section has been devoted to an estimate of the effect of impact-parameter correlation on the multiple scattering of penetrating molecules. That effect is by and large unrelated to Coulomb explosion, but some attention is indicated since it is an unavoidable feature in all scattering phenomena involving molecular ions.

*Argonne Fellow from Odense University

b. Scattering and Stopping of Swift Diatomic Molecules under Coulomb Explosion (P. Sigmund*)

The scattering and stopping of the fragments of a fast diatomic molecule under Coulomb explosion has been analyzed theoretically. The central assumption in the scheme is the dominance of Coulomb explosion, while electronic stopping (including wake forces) and elastic scattering are treated as perturbations. Charge exchange has been neglected. Coulomb images of penetration phenomena are heavily distorted. For small penetrated layer thicknesses, 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 us to scale velocity distributions valid in the absence of Coulomb explosion into distributions allowing for Coulomb explosion. Applications concern the shift in ring pattern due to electronic stopping, the lateral broadening due to multiple scattering, and the effect of zero-point motion on the Coulomb image of a molecule.

*Argonne Fellow from Odense University

ACCELERATOR FACILITIES FOR ATOMIC PHYSICS

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. P. L. Cowan of our group is responsible for this beamline under the terms of an agreement with NIST (R. D. Deslattes).

A technical support group is available to assist with atomic physics experiments on these accelerators and for other experiments. The staff of this group includes: B. J. Zabransky, a Mechanical Engineer who is in charge of design, technical improvements, and the setup of experimental beam lines; R. L. Amrein and A. E. Ruthenberg who are operators of the Dynamitron and work on technical projects at each of the other accelerators; C. Kurtz whose primary responsibility is BLASE and the synchrotron-based program, and helping with maintenance and technical design at the other facilities. Kurtz and Zabransky 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.

Operations at ATLAS (R. W. Dunford, B. J. Zabransky, R. L. Amrein, and A. E. Ruthenberg)

The atomic physics beam line set up at the ATLAS heavy-ion accelerator 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 determines precisely 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. A third region which will be used to study interactions of ATLAS beams with a fullerene target is currently under construction.

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 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, as described in Section V of this report.

Substantial efforts have been directed toward complying with electrical, optical, and other safety standards.

Operation of the Dynamitron Facility (R. L. Amrein, E. P. Kanter, A. E. Ruthenberg, and B. J. Zabransky)

The Dynamitron is a high-current stabilized 5-MV accelerator that can provide singly-charged beams of most atomic ions and many molecular ions. 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 can 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.

OTHER EDUCATIONAL ACTIVITIES IN THE PHYSICS DIVISION

The education of the next generation of scientists is an important component of the Division's programs. Many aspects of this activity are described in this Report in connection with the specific programs, most of which have an educational component involving university personnel. In addition, university user activities at ATLAS are listed separately, and lists of postdocs, and of graduate and undergraduate students involved in various activities are given. There are to additional programs related to education which are of importance to the Division but do not fit in the above categories: one is concerned with enhancing minority involvement in science, in particular in physics; the other involves scientific support for exhibits and outreach programs in connection with the SciTech Museum in nearby Aurora. These activities are described below.

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

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, 33 applications were received for the summer program in 1992. A total of 18 offers were made for the Summer Research Participation program in conjunction with Argonne's Department of Educational Programs; 10 students participated during the summer. Of these, five students were engaged in nuclear physics research in the Physics Division, (4 at ATLAS, 1 in theory), with the other students participating in the programs in related areas, e.g. at the Advanced Photon Source. 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.

B. Scientific Support of SciTech Museum Exhibits and Outreach Programs (M. Peshkin)

SciTech (Science and Technology Interactive Center) is a small, young hands-on science museum, one of some four hundred in the world that follow the inspiration of San Francisco's Exploratorium. SciTech is located in Aurora, Illinois, about fifty miles west of Chicago. It serves a diverse constituency including prosperous suburbs and economically disadvantaged minority communities in Aurora and Chicago. This museum, like the other science and technology interactive centers, aspires to contribute to the country's scientific literacy initiative. SciTech does that by offering hands-on experiences both on the museum floor and in outreach programs extended toward schoolchildren, teachers, and other groups. In this, SciTech is being aided substantially by the City of Aurora, by Argonne National Laboratory and Fermi National Accelerator Laboratory, by technological industries in Chicago's western suburbs, and by numerous volunteer exhibit developers and builders.

Argonne's participation is focussed primarily on two activities which offer the opportunity to have a national impact on technology centers: the development of exhibits to make modern science understandable to the museum's audience, and a unique outreach program directed toward schools and other community organizations. We also participate in the development and improvement of general floor exhibits and especially of their explanatory signs, and Argonne's Laboratory Director Alan Shriesheim serves on the museum's Board of Directors.

B.a Outreach Programs (M. Peshkin)

The "Discover and Explore" program (D&E), supported in part by the Illinois Department of Education, takes groups of about ten exhibits to some seventy area schools, including a substantial number of schools that serve economically or educationally disadvantaged minority communities. Each group of hands-on exhibits focuses on a single subject, such as light or sound. In the schools, each fourth, fifth, and sixth grade class has an hour to experiment with the exhibits guided by their own teachers, followed after a few days by a second hour with a SciTech explainer, who is typically an elementary school teacher. SciTech provides written handouts for the children and their teachers and trains the teachers and the explainers. The Argonne contribution in this is participation in the selection or design of some of the exhibits, editing of the handouts for scientific accuracy and clarity, and educating the explainers and sometimes the teachers. A second outreach program, supported by DOE, consists of SciTech clubs for girl scouts. The girls construct exhibits for use on the museum floor with the guidance of a SciTech mentor. The Argonne contribution is to advise the mentor in matters of science and presentation. A third, new, program is a collaboration of five science centers around the State of Illinois to develop exhibits modeled on D&E to first and second grade children and their teachers. These programs, which are unique to our knowledge, have attracted national attention in the museum community and exploratory conversations about generalizing them to Illinois or the country have been encouraged by the appropriate funding agencies.

B.b. Modern Physics Exhibitions (D. Henderson and M. Peshkin)

Traditional museums are weak in modern science. SciTech has been addressing that problem by designing and constructing major exhibitions to present modern physics accessibly to a museum audience. The plans for these exhibitions will be made available free to other museums, or they will be copied for other museums at cost. At present, three such exhibitions are in different parts of the pipeline:

"Building Blocks of the Universe" has been developed in collaboration with the Ohio's Center of Science and Industry (COSI) an established museum in Columbus, Ohio, and funded principally by the National Science Foundation. This group of hands-on exhibits, which takes the visitor from the macroscopic world to quarks, includes Brownian motion, an active model atom that makes transitions when excited with the resonance frequencies, line spectra, a radioactive decay model, and an unusual exhibit based on the chart of the nuclides, plus graphic materials. The SciTech contribution to the collaboration has been the design and construction of the working parts of the exhibits and the scientific component of the graphic materials. Argonne's contribution to that has been primarily assuring the accuracy and relevance of all the graphic materials and computer-presented informational material, and initiating and writing some of them. This exhibit was completed, except for fine tuning, in FY 1993 and is now serving the public in the exhibition's initial form.

"$E=mc^2$" is currently being developed in collaboration with COSI and funded principally by DOE. The SciTech contribution is the scientific component of the exhibition. The Argonne work has consisted of contributions to the conception and design of the project, writing the proposal for DOE support, actual development and construction of the working parts of the exhibit, and seeking needed non-federal matching funds to complete the project. The two major components of the exhibition are 1) a hands-on display of positron annihilation into two gamma rays whose energies are measured, with the geometry of the detectors controlled by the visitor; and 2) creation of pairs by gamma rays in a diffusion cloud chamber, with magnetic fields and other parameters controlled by the visitor. The plan is to create three copies of this exhibit, one each for COSI and SciTech, and a traveling version for other museums. In FY 1993, construction of a prototype for the positron decay will be completed and tested on the SciTech museum floor. We expect to complete the two museum copies of the entire exhibit late in FY 1994 and to make the traveling copy in FY 1995. Construction of the traveling copy depends upon matching funds not yet in hand.

"Quantum Mechanics" is an exhibition currently in the conceptual design stage. In FY 1993 we expect to form a partnership with area high school teachers and with them to write a grant proposal near the end of the fiscal year. Our intention is to create exhibits to demonstrate some of the main features of quantum mechanics suitably for high school labs and for demonstrations in the museum, and to construct one copy of the exhibition for SciTech and one or more to travel to high schools. Ideally, we would like to start construction of prototypes in FY 1994 and complete the project in FY 1995.

STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the staff of the Physics Division for the year ending March 31, 1993. 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., University of Tennessee, 1987
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
|| Jerry A. Nolen, Jr., Ph.D., Princeton University, 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
‡‡ Kenneth Teh, Ph.D., Vanderbilt University, 1988
§§ Alan H. Wuosmaa, Ph.D., University of Pennsylvania, 1989
Benjamin Zeidman, Ph.D., Washington University, 1957

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* On assignment at SUNY until August 1993.
† In charge of ATLAS operations and accelerator development until April 1, 1992. Retired September 30, 1992. Post-retirement research participant as of October 1, 1992.
‡ On leave at the University of California, Berkeley until October 1, 1993.
§ ATLAS User Program Administrator.
¶ Director of the Physics Division.
|| Director of the ATLAS Facility as of April 1, 1992.
** ATLAS Operations Manager
†† Associate Director of the Physics Division. Joint appointment with the University of Chicago.
‡‡ Joined the Physics Division in January 1993.
§§ Enrico Fermi Scholar until November 1992.

Other Experimental Staff Members

- * Melvin S. Freedman, Ph.D., University of Chicago, 1942
- * Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937
- † Frank J. Lynch, B.S., University of Chicago, 1944
- * 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

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* Post-retirement research participant.
† Post-retirement research participant. Deceased March 10, 1993.
‡ On loan at the University of Michigan October-December 1992.
§ Resident Associate Guest Appointee from the University of Illinois, Chicago
¶ Post-retirement research participant. Deceased September 5, 1993.
‖ Special Term Appointee from the University of Illinois, Urbana.

ATOMIC AND MOLECULAR PHYSICS

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

‡ William J. Childs, Ph.D., University of Michigan, 1956
‡ F. Paul Mooring, Ph.D., University of Wisconsin, 1951
‡ Gilbert J. Perlow, Ph.D., University of Chicago, 1940

TEMPORARY APPOINTMENTS

TERM APPOINTMENTS

Torben Lauritsen, Ph.D., State University of New York, 1990
David H. Potterveld, Ph.D., Caltech, 1988

POSTDOCTORAL APPOINTEES

Song Cheng (from Kansas State University, Manhattan, Kansas):
Atomic physics at ATLAS.
(August 1991--)

Kevin Coulter (from Princeton Unversity, Princeton, New Jersey):
Medium-energy physics.
(December 1988--March 1993)

Martin Freer (from Birmingham University, Birmingham, UK):
Heavy-ion physics at ATLAS.
(April 1991--April 1993)

Richard Harkewicz (from Michigan State University, E. Lansing, Michigan):
Accelerator development and research at ATLAS.
(March 1992--)

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* Joint Appointment with Weizmann Institute of Science, Rehovot, Israel.
† On sabbatical at JILA until September 1993.
‡ Post-retirement research participant.

Roland Henry (from Rutgers University, New Brunswick, New Jersey):
Heavy-ion physics at ATLAS.
(January 1992--)

Cathleen Jones (California Institute of Technology, Pasadena, California):
Medium-energy physics.
(October 1992--)

*Torben Lauritsen (from SUNY, Stony Brook, NY):
Nuclear physics research at ATLAS.
(June 1990--October 1992)

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 physics at ATLAS.
(August 1991--March 1993)

Vassilios Papavassiliou (from Yale University, New Haven, Connecticut):
Medium-energy physics research.
(May 1991--)

Heikki Penttila (from University of Jyvaskyla, Finland):
Research with the FMA at ATLAS
(October 1992--)

Bernard Matthew Poelker (from Northwestern University, Evanston Illinois):
Medium-energy physics research.
(January 1992--)

Martin Rhein (Institut fur Kernphysik, Darmstadt, Germany):
Heavy-ion physics at ATLAS.
(January 1993--)

†Rocco Schiavilla (from University of Illinois, Urbana, IL):
Nuclear theory studies.
(May 1990--July 1992)

‡Alan H. Wuosmaa (from University of Pennsylvania, Philadelphia, Pa):
Heavy-ion physics at ATLAS.
(September 1989--November 1992)

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* Staff Term Appointment as of October 1992.
† Enrico Fermi Scholar.
‡ Enrico Fermi Scholar. Joined regular staff in November 1992.

TECHNICAL AND ENGINEERING STAFF
(and areas of activity)

* Kevin G. Bailey (B.S. University of Nebraska, 1989).
SOS construction for CEBAF.

† Brian T. Batzka,(B.S. University of Houston, 1992).
ATLAS operator.

Peter J. Billquist
ECR heavy-ion source, ATLAS operation.

John M. Bogaty (A.A.S. DeVry, 1961).
Electrical systems, ATLAS operation and development.

‡ Benny G. Clifft (A.S.E.E., DeVry, 1959).
Electrical systems, ATLAS operation and development.

Joseph Falout (B.S.M.E. University of Illinois, 1970).
Experimental equipment design.

§ Jack Goral (M.S.M.E. Wroclaw Institute, Poland, 1978).
Experimental equipment design.

John P. Greene (M.S. DePaul University, 1982).
Target preparation.

Ray E. Harden (A.A.S. Milwaukee School of Engineering, 1957).
ATLAS operator

Dale J. Henderson (B.S. Elmhurst College, 1951).
Detector development, technical assistance, heavy-ion physics.

James M. Joswick (A.A.S. Milwaukee School of Engineering, 1964).
ATLAS experimental equipment maintenance, technical assistance, heavy-ion physics.

Raymond B. Kickert
ATLAS experimental equipment maintenance, technical assistance, heavy-ion physics.

Robert Kowalczyk (M.S. Northeastern Illinois University, 1983).
Technical assistance, medium-energy physics.

Charles A. Kurtz (M.S. University of Arkansas, 1984).
Technical assistance, atomic physics.

¶ Paul Markovich (B.S. Purdue University, 1972).
Surface chemistry, ATLAS development and operation.

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* Joined the Physics Division in January 1993. Term appointment.
† Joined the Physics Division in February 1993. Term Appointment.
‡ Transferred from the Chemistry Division in November 1992.
§ Transferred to APS Division in March 1992.
¶ Retired in January 1993. Special Term Appointee as of February 1993.

* Thomas Moog (B.A., Princeton University, 1975).
Computer operations group.

Thomas P. Mullen (B.S. Marquette University, 1966).
Division ESH/QA engineer.

Floyd Munson, Jr. (A.A.S. DeVry, 1966).
Control system for ATLAS.

Kirt Nakagawa (B.S. University of Illinois, 1988).
ATLAS operator.

Bruce G. Nardi (A.A.S. Morton Jr. College, 1967; A.A.S. DeVry, 1969).
Electronics design and maintenance.

† John F. Sasso (B.A. University of Chicago, 1987).
Computer operations group.

James R. Specht (A.A.S. DeVry, 1964).
Cryogenics engineer. ATLAS development and operation.

Philip Strickhorn (B.S. DeVry, 1990).
Electrical and technical assistance with ATLAS operations.

‡ Brian J. Tieman (B. A. North Central College, 1992).
ATLAS operator.

Ian R. Tilbrook (B.S. Pennsylvania State University, 1987).
ATLAS operator.

Richard Vondrasek (B.S. University of Illinois, 1990).
ATLAS operator.

Gregory Wiemerslage (B.S. Elmhurst College, 1990).
Technical assistance with ATLAS operations.

Philip R. Wilt (Johnstown Technical School 1973).
Electronics design and maintenance..

§ Bruce J. Zabransky (M.S. University of Illinois, Chicago, 1973).
Dynamitron operation.

¶ Anthony R. Zeuli (B.A. Hamline University, 1990).
Technical assistance. Weak interactions physics.

Gary P. Zinkann (B.S. DeVry, 1975).
Superconducting resonators and linac maintenance, for ATLAS operations.

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* Terminated August 1992.
† Terminated July 1992.
‡ Term appointment.
§ In charge of Dynamitron operation.
¶ On leave of absence until June 1993.

ADMINISTRATIVE STAFF

* Allan Bernstein, M.B.A., Rosary College, 1986
† James E. Nelson, B.A., University of Illinois, 1975

VISITORS AND STUDENTS

LONG-TERM VISITORS (at Argonne more than 4 months)

Nemitala Added (University of Sao Paulo, Brazil):
ATLAS development.
(April 1991--)

Daniel Ashery (Tel Aviv University, Jerusalem, Israel):
Medium-energy physics research.
(July 1992--)

Dan Berkovits (Hebrew University, Jerusalem, Israel):
Nuclear astrophysics research at ATLAS.
(February 1992--August 1992)

Marcello D. Farraretto (University of Sao Paulo, Brazil):
ATLAS development.
(October 1990-September 1992)

Cheng-lie Jiang (Institute of Atomic Energy, Beijing, China):
Heavy-ion physics studies.
(October 1992--)

‡ Nora Mansour (Western Michigan University, Kalamazoo, Michigan):
Atomic physics at synchrotron light sources.
(October 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--October 1992)

Tsuguhisa Sekioka (Himeji Institute of Technology, Japan):
Atomic physics with synchrotrons.
(April 1992--)

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* Assistant Director of the Physics Division.
† Manager, Division Operations.
‡ Guest Faculty Research Participant.

* Peter Sigmund (Odense University, Odense, Denmark):
Particle penetration phenomena.
(January 1993)

Francesca Soramel (University of Padova, Italy):
Heavy-ion research at ATLAS.
(September 1991--September 1992)

Dagoberto Stucker (University of Sao Paulo, Brazil):
Linac development.
(July 1992--February 1993)

† Carol Tanner (University of Notre Dame, Indiana):
Atomic physics at BLASE.
(March 1992--)

Dmitri Toporkov (Institute for Nuclear Physics, Novosibirsk, UR):
Medium-energy physics research.
(February 1992--August 1992)

FACULTY VISITORS

†Donald Beck (Michigan Technical University, Houghton, Michigan):
Accelerator-based atomic physics.
(June-July 1992)

‡Stuart Brekke (Schurz High School, Chicago, Illinois):
Atomic physics research.
(June-August 1992)

Vladimir Dmitriev (Institute of Nuclear Physics, Novosibirsk, UR):
Theoretical physics studies.
(May-June 1992)

Alexander Dorokhov (Joint Institute for Nuclear Research, Moscow, UR):
Theoretical physics studies.
(June-July 1992)

Jose-Luis Egido (University of Madrid, Madrid, Spain):
Theoretical physics studies.
(July 1992)

Gvirol B. Goldring (Weizmann Institute of Science, Rehovoth, Israel):
Research with the FMA at ATLAS.
(July-September 1992)

* 1988-89 Argonne Fellow. Interrupted appointment completed in 1993.
† Faculty Research Participant.
‡ Department of Energy Teacher Research Associate Program.

*Edward Hohman (York Township High School, Lyons, Illinois):
Summer student coordinator.
(June-August 1992)

Pankaj Jain (University of Kansas, Manhattan, Kansas):
Theoretical physics studies.
(July 1992)

Hans J. Korner (Technical University of Munich, Germany):
Heavy-ion research at ATLAS.
(May 1992)

Gabrielle Korner (Technical University of Munich, Germany):
Heavy-ion research at ATLAS.
(May 1992)

†Robert Lewis (University of Michigan, Ann Arbor, Michigan):
Atomic physics at ATLAS.
(May-June 1992)

†Arthur E. Livingston (University of Notre Dame, Notre Dame, Indiana):
Atomic physics studies.
(June-July 1992)

‡Kristen Newton (Cambridge Rindge and Latin High School, Cambridge, Massachusetts):
Medium-energy physics studies.
(June-August 1992)

Michael Paul (Hebrew University, Jerusalem, Israel):
Heavy-ion research at ATLAS.
(October 1992)

†Akunuri Ramayya (Vanderbilt University, Nashville, Tennessee):
Heavy-ion research at ATLAS.
(May-June 1992)

RESIDENT GRADUATE STUDENTS

Ian Bearden (Purdue University, W. Lafayette, Indiana):
Heavy-ion research at ATLAS.
(January 1990--   )

Kevin Beyer (Michigan State University, E. Lansing, Michigan):
Heavy-ion research at ATLAS.
(August 1992--   )

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* Faculty Research Participant. Summer Student Coordinator.
† Faculty Research Participant.
‡ Department of Energy Teacher Research Associate Program.

Kanwarjit S. Bindra (Vanderbilt University):
FMA development at ATLAS.
(May 1990--)

Kin Chi Chan (Yale University, New Haven, Connecticut):
APEX experiment at ATLAS.
(June 1992--)

Wonkyun Chung (University of Notre Dame):
FMA development at ATLAS.
(August 1991--February 1992)

Mohammad Talebian Darzi (University of Illinois, Chicago, Illinois):
Atomic physics research.
(January 1993--)

John C. Gehring (University of Chicago, Chicago, Illiniois):
Heavy-ion research at ATLAS.
(June 1990--)

Timothy J. Graber (University of Illinois, Chicago)::
Coulomb-explosion studies.
(October 1989--)

Kihun Joh (Michigan State University):
ATLAS development.
(June 1992--)

Nicholas Kaloskamis (Yale University, New Haven, Connecticut):
APEX experiment at ATLAS.
(November 1991--)

Kris Kukla (University of Notre Dame):
Atomic physics research.
(July 1992--)

Manquing Liu (Queen's University, Kingston, Ontario, Canada):
APEX experiment at ATLAS.
(September 1992--)

Dante Roa (Florida State University):
Research with APEX at ATLAS.
(May 1992--)

Jamal Suleiman (University of Illinois, Chicago, Illinois):
Atomic physics research.
(October 1991--)

Mark Wolanski (University of Chicago, Chicago, Illinois):
Weak interaction studies.
(July 1991--)

Guest Graduate Students

Jeffrey Hangst (University of Chicago, Chicago, Illinois):
Ordered ion beams.
(October 1991-September 1992)

Shuichi Hasegawa (University of Tokyo, Japan):
Atomic physics research.
(May 1992)

Zhengtian Lu (University of Chicago, Chicago, Illiinois):
Weak interactions studies.
(November 1991--)

Aloy Perera (University of Rochester, Rochester, New York):
APEX experiment at ATLAS.
(August 1991--)

Robert Rafac (University of Notre Dame, Notre Dame, Indiana):
Atomic physics research.
(March 1992--)

Thih-Yuen Tung (Northwestern University, Evanston, Illinois):
Nuclear physics experiments.
(September 1987--December 1992)

Zhou Yu (Northwestern Unviersity, Evanston, Illinois):
Intermediate-energy physics.
(September 1987--)

UNDERGRADUATE STUDENTS

Jonathan Arndt (University of Illinois-Urbana)
Richard Balsano (Oberlin College)
Michael Bennett (Florida A&M University)
Elizabeth Besenfelder (Washington & Lee University)
Kevin Beyer (Loyola University)
Germeline L. Calagday (California State University)
Sandra Collins (Lawrence University)
Sihon Crutcher (Tuskegee University)
Badi Ebrahimifard (University of Connecticut)
Daniel Felten (Howard University)
Melanie Felton (Andrews University)
Christopher Fischer (Washington University)
David Flory (University of Michigan-Flint)
Nels Freed (Andrews University)
Jennifer Gerbi (Bard College)
Steven Harfenist (Buffalo State College)
Taliver Heath (Florida State University)
Jeffrey Katz (University of North Texas)
Robert Kaye, Jr. (Florida State University)
Kevin Knaus (University of Chicago)
Jamie Kustak (Georgetown University)
Gregory Matous (Western Michigan University)
Justin L. Mortara (University of Chicago)
Rebecca Rdesinski (Bloomsburg University)

Brian Rutherford (College of St. Francis)
Kenneth St. Amant (Oklahoma State University)
Joseph Stacy (Norfold State University)
Christopher Stepanek (College of St. Francis)
David Sowinski (Lewis University)
Jamal Suleiman (University of Illinois, Chicago)
Kristie Thomas (Tougaloo College)
Brian J. Tieman (North Central College)
Michael Torelli (Jacksonville University)
James Wisniewski (Purdue University)

PRE-COLLEGE PROGRAM (Just Graduated from High School)
(June--August 1992)

Richard Ainsworth (Joliet Township High School)
Elizabeth Brown (Oak Park/River Forest High School)
Jonathan Hall (Naperville Central High School)
Jay Kreibich (York Community High School)
Daniel Lee (Kenwood Academy)

PUBLICATIONS FROM APRIL 1, 1992 THROUGH MARCH 31, 1993

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HEAVY-ION RESEARCH

Evidence for Alpha-particle Chain Configuration in ^{24}Mg
A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, B. G. Glagola, T. Happ, D. J. Henderson, P. Wilt, and I. G. Bearden
Phys. Rev. Lett. 68, 1295-1298 (1992)

Yrast Isomers in Tin Nuclei from Heavy Ion Collisions and the $\nu h_{11/2}$ Subshell Filling
R. Broda, R. H. Mayer, I. G. Bearden, Ph. Benet, P. J. Daly, Z. W. Grabowski, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, E. F. Moore, S. Lunardi, and J. Blomqvist
Phys. Rev. Lett. 68, 1671 (1992)

Feeding of Superdeformed Bands: The Mechanism and Constraints on Band Energies and the Well Depth
T. Lauritsen, Ph. Benet, T. L. Khoo, K. Beard, I. Ahmad, M. P. Carpenter, P. J. Daly, M. W. Drigert, U. Garg, P. B. Fernandez, R. V. F. Janssens, E. F. Moore, F. L. H. Wolfs, and D. Ye
Phys. Rev. Lett. 69, 2479-2482 (1992)

Quasielastic Scattering of ^{11}Li and ^{11}C from ^{12}C at 60 MeV/Nucleon
J. J. Kolata, M. Zahar, R. Smith, K. Lamkin, M. Belbot, R. Tighe, B. M. Sherrill, N. A. Orr, J. S. Winfield, J. A. Winger, S. J. Yennello, G. R. Satchler, and A. H. Wuosmaa
Phys. Rev. Lett. 69, 2631-2634 (1992)

Phase Transitions in Anisotropically Confined Ionic Crystals
J. P. Schiffer
Phys. Rev. Lett. 70, 818 (1993)

Dynamic Moment of Inertia of the ^{192}Hg Superdeformed Band at High Rotational Frequencies
T. Lauritsen, R. V. F. Janssens, M. P. Carpenter, E. F. Moore, I. Ahmad, P. B. Fernandez, T. L. Khoo, J. A. Kuehner, D. Prevost, J. C. Waddington, U. Garg, W. Reviol, D. Ye, and M. W. Drigert
Phys. Lett. B279, 239-243 (1992)

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
Phys. Rev. C 44, (1991)

Low-Lying Excitations in ^{176}Yb and ^{180}Hf from ($\vec{p}$,p') Scattering at E_p = 98.4 MeV
R. Perrino, R. De Leo, A. D. Bacher, G. T. Emery, C. W. Glover, H. Nann, C. Olmer, R. V. F. Janssens, and S. Y. van der Werf
Phys. Rev. C 45, 1017 (1992)

Fusion Evaporation-residue Cross Sections for ^{28}Si + ^{40}Ca at E(^{28}Si) = 309, 397, and 452 MeV
M. F. Vineyard, J. S. Bauer, J. F. Crum, C. H. Gosdin, R. S. Trotter, D. G. Kovar, C. Beck, D. J. Henderson, R. V. F. Janssens, B. D. Wilkins, C. F. Maguire, J. F. Mateja, F. W. Prosser, and G. S. F. Stephans
Phys. Rev. C 45, 1784 (1992)

Elastic Scattering and Quasielastic Transfer in the System $^{76,82}Se + ^{192,198}Pt$
F. L. H. Wolfs, K. E. Rehm, W. C. Ma, J. P. Schiffer, and T. F. Wang
Phys. Rev. C 45, 2283-2289 (1992)

Yrast Decays in ^{43}K
R. L. Kozub, C. R. Bybee, M. M. Hindi, J. F. Shriner, Jr., R. Holzman, R. V. F. Janssens, T. L. Khoo, W. C. Ma, M. W. Drigert, U. Garg, and J. J. Kolata
Phys. Rev. C 46, 1671 (1992)

Double Blocking in the Superdeformed ^{192}Tl Nucleus
Y. Liang, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, R. Henry, T. L. Khoo, T. Lauritsen, F. Soramel, S. Pilotte, J. M. Lewis, L. L. Riedinger, C.-H. Yu, U. Garg, W. Reviol, and I. G. Bearden
Phys. Rev. C 46, R2136-2139 (1992)

Multiple Band Structures in ^{191}Hg
D. Ye, K. B. Beard, U. Garg, R. V. F. Janssens, M. P. Carpenter, I. Ahmad, T. L. Khoo, E. F. Moore, F. L. H. Wolfs, Ph. Benet, Z. W. Grabowski, and M.W. Drigert
Nucl. Phys. A537, 207 (1992)

Shape Driving Effects in ^{193}Tl from the Spectroscopy of Yrast and Near-Yrast States
W. Reviol, M. P. Carpenter, U. Garg, R. V. F. Janssens, I. Ahmad, I. G. Bearden, Ph. Benet, P. J. Daly, M. W. Drigert, P. B. Fernandez, T. L. Khoo, E. F. Moore, S. Pilotte, and D. Ye
Nucl. Phys. A548, 331-352 (1992)

Characterization of the Superdeformed Band in ^{189}Hg
I. G. Bearden, R. V. F. Janssens, M. P. Carpenter, E. F. Moore, I. Ahmad, A. M. Baxter, Ph. Benet, P. J. Daly, M. W. Drigert, P. B. Fernandez, U. Garg, Z. W. Grabowski, T. L. Khoo, T. Lauritsen, W. Reviol, and D. Ye
Z. Phys. A 341, 491 (1992)

New $19/2^+$ Isomers in ^{119}Sn, ^{121}Sn and ^{123}Sn
R. H. Mayer, B. Formal, R. Broda, I. G. Bearden, Z. W. Grabowski, S. Lunardi, P. J. Daly, T. Lauritsen, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, and Y. Liang
Z. Phys. A. Hadrons and Nuclei 342, 247 (1992)

Inelastic Scattering and Nucleon Transfer in the System $^{232}Th+^{206}Pb$ near the Coulomb Barrier
G. Eckert, K. Stelzer, R. O. Nelson, Th. W. Elze, Th. Happ, H. J. Wollersheim, H. Emling, H. Grein, W. Henning, R. Kulessa, E. Lubkiewicz, and Ch. Lauterbach
Z. Phys. A, Hadrons and Nuclei 343, 267-278 (1992)

Compton Suppression Tests on Ge and BGO Prototype Detectors for GAMMASPHERE
A. M. Baxter, T. L. Khoo, M. E. Bleich, M. P. Carpenter, I. Ahmad, R. V. F. Janssens, E. F. Moore, I. G. Bearden, J. R. Beene, and I. Y. Lee
Nucl. Instrum. Methods A317, 101-110 (1992)

Response of BGO Detectors to Photons of 3-50 MeV Energy
T. Matulewicz, W. Henning, H. Emling, R. Freifelder, H. Grein, E. Grosse, N. Herrman, P. Holzmann, R. Kulessa, R. S. Simon, H. J. Wollersheim, B. Schoch, J. Vogt, M. Wilhelm, J. V. Kratz, R. Schmidt, and R. V. F. Janssens
Nucl. Instrum. Methods A325, 216 (1993)

Startup of the Fragment Mass Analyzer at ATLAS
C. N. Davids, B. B. Back, K. Bindra, D. J. Henderson, W. Kutschera,
T. Lauritsen, Y. Nagame, P. Sugathan, A. V. Ramayya, and W. B. Walters
Proceedings of the 12th International Conference on Electromagnetic Isotope Separators & Techniques Related to their Applications, Sendai, Japan, 2-6 September 1991; Nucl. Instrum. Methods B70, 358-365 (1992)

Energy Compensation of an ISOLDE-type Isotope Separator
Cary N. Davids
Nucl. Instrum. Methods B70, 435-440 (1992)

Half-Life Determination of ^{41}Ca and Some Other Radioisotopes
Walter Kutschera, Irshad Ahmad, and Michael Paul
Radiocarbon 34, 436-446 (1992)

Sub-barrier Fusion: An Experimental Review
R. R. Betts
International Symposium: "Towards a Unified Picture of Nuclear Dynamics", Nikko, Japan, 6-8 June 1991, (AIP, New York), p. 3

The Isospin Laboratory: Research Opportunities with Radioactive Nuclear Beams
R. F. Casten, J. M. D'Auria, C. N. Davids, J. D. Garrett, J. M. Nitschke, B. M. Sherrill, D. J. Vieira, M. Wiescher, and E. F. Zganjar
LALP 91-51 (Los Alamos National Laboratory, 1991, Los Alamos, NM)

Superdeformation: An Experimental Review
R. V. F. Janssens
Workshop on Nuclear Shapes and Nuclear Structure at Low Excitation Energies, Cargese, France, June 3-7, 1991, Edited by M. Vergnes et al., (Plenum, New York, 1992) Vol. 289, pp. 299-313

Nuclear Structure Studies Far Off Stability Using Radioactive Beams and Inverse Kinematics
A. Weiss, P. Egelhof, B. Franzke, H. Geissel, A. Gruber, W. Henning,
G. Kraus, A. Magel, G. Munzenberg, F. Nickel, M. Hamm, J. V. Kratz,
F. Friese, A. Gillitzer, H. J. Korner, M. Peter, J. P. Schiffer,
L. V. Chulkov, M. S. Golovkov, and A. A. Ogloblin
Proceedings of the XXX International Winter Meeting on Nuclear Physics, Bormio, Italy, 27 January - 1 February, 1992, pp. 447-451 (1992)

Shape Coexistence at High Spin in ^{188}Hg
I. G. Bearden, M. P. Carpenter, A. M. Baxter, R. V. F. Janssens, I. Ahmad, Ph. Benet, P. J. Daly, M. W. Drigert, P. B. Fernandez, B. Fornal, U. Garg, Z. W. Grabowski, T. L. Khoo, R. M. Mayer, E. F. Moore, W. Reviol, and D. Ye
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada,, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 18 (1992)

Shape-Driving Effects in ^{193}Tl from the Spectroscopy of Yrast and Near-Yrast States
W. Reviol, M. P. Carpenter, U. Garg, R. V. F. Janssens, I. Ahmad,
I. G. Bearden, Ph. Benet, P. J. Daly, M. W. Drigert, P. B. Fernandez,
T. L. Khoo, E. F. Moore, S. Pilotte, and D. Ye
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada,, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 24 (1992)

The Structure of the Light Polonium Nuclei
L. A. Bernstein, J. A. Cizewski, R. G. Henry, L. P. Farris, H. Q. Jin, M. P. Carpenter, T. L. Khoo,
R. V. F. Janssens, T. Lauritsen, I. Bearden, and D. Ye
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 31 (1992)

Calculations of the Decay of Superdeformed Bands and Search for the γ Rays Connecting Superdeformed and Normal States
T. Lauritsen, T. L. Khoo, E. F. Moore, I. Ahmad, M. P. Carpenter, P. Fernandez, R. V. F. Janssens,
Y. Liang, M. Freer, A. Wuosmaa, Ph. Benet, I. Bearden, P. J. Daly, B. Fornal, D. Ye, U. Garg, and
M. W. Drigert
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada,, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 53 (1992)

Feeding of the Superdeformed Band in ^{192}Hg: The Mechanism and Constraints on the Superdeformed Band Energies and Well Depth
Ph. Benet, T. Lauritsen, T. L. Khoo, I. Ahmad, K. Beard, I. G. Bearden, M. P. Carpenter, P. Daly,
M. W. Drigert, P. B. Fernandez, U. Garg, R. V. F. Janssens, Y. Liang, E. F. Moore, W. Reviol,
and D. Ye
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 54 (1992)

Higher Superdeformed Band Members in ^{190}Hg: Evidence for a Band Interaction?
I. G. Bearden, R. V. F. Janssens, M. P. Carpenter, I. Ahmad, P. J. Daly, M. W. Drigert, U. Garg,
T. L. Khoo, T. Lauritsen, W. Reviol, and R. Wyss
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 55 (1992)

"Identical" Superdeformed Bands in ^{192}Tl
Y. Liang, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, R. Henry, T. L. Khoo, T. Lauritsen,
S. Pilotte, J. M. Lewis, L. L. Riedinger, C. H. Yu, U. Garg, W. Reviol, and I. G. Bearden
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 56 (1992)

Entrance-Channel Dependence in the Population of the Superdeformed Bands in ^{192}Hg
F. Soramel, T. L. Khoo, R. V. F. Janssens, I. Ahmad, M. P. Carpenter, T. Lauritsen, Y. Liang, B. Fornal, I. Bearden, Ph. Benet, P. J. Daly, Z. W. Grabowski, R. Maier, D. Ye,U. Garg, W. Reviol, and M. W. Drigert
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 2, p. 59 (1992)

Statistical Gamma Transitions in ^{174}Hf
L. P. Farris, M. J. Brinkman, J. A. Cizewski, R. G. Henry, C. S. Lee, T. L. Khoo, R. V. F. Janssens, E. F. Moore, M. P. Carpenter, I. Ahmad, T. Lauritsen, J. J. Kolata, K. B. Beard, D. Ye, U. Garg, M. S. Kaplan, J. Y. Saladin, and D. Winchell
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 2, p. 71 (1992)

Superdeformed Bands in ^{191}Tl
S. Pilotte, C.-H. Yu, J. M. Lewis, L. L. Riedinger, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, F. Soramel, and I. G. Bearden
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 78 (1992)

Improvement in the Energy Resolution of Large Ge Detectors by Software Techniques
M. P. Carpenter, T. L. Khoo, M. Bleich, I. Ahmad, A. M. Baxter, R. V. F. Janssens, F. L. H. Wolfs, D. Ye, and I. G. Bearden
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 1, p. 125 (1992)

Superdeformed Bands in ^{191}Tl
S. Pilotte, J. M. Lewis, L. L. Riedinger, C.-H. Yu, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, F. Soramel, and I. G. Bearden
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23 1992, AECL-10613, Vol. 2, p. 2 (1992)

Higher Superdeformed Band Members in ^{190}Hg: Evidence for a Band Interaction
M. W. Drigert, U. Garg, T. L. Khoo, T. Lauritsen, Y. Liang, W. Reviol, and R. Wyss
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23 1992, AECL-10613, Vol. 2, p. 10 (1992)

The Onset of Collectivity in ^{196}Po
L. A. Bernstein, J. A. Cizewski, H. Q. Jin, R. G. Henry, L. P. Farris,T. L. Khoo, M. P. Carpenter, R. V. F. Janssens, T. Lauritsen I. G. Bearden, and D. Ye
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992 AECL-10613, Vol. 2, p. 127 (1992)

Double Blocking in the Superdeformed ^{192}Tl Nucleus
Y. Liang, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, R. Henry, T. L. Khoo, T. Lauritsen, F. Soramel, S. Pilotte, J. M. Lewis, L. L. Riedinger, C. H. Yu, U. Garg, W. Reviol, and I. G. Bearden
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992 AECL-10613, Vol. 2, p. 207 (1992)

Spectroscopy of ^{96}Ru and ^{98}Ru: Structures of Varied Character at N ≥ 52
W. Reviol, U. Garg, B. F. Davis, A. Aprahamian, S. Naguleswaran, J. C. Walpe, D. Ye, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, and Y. Liang
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 2, p. 240 (1992)

Compton Suppression Tests on Ge and BGO Prototype Detectors for GAMMASPHERE
A. M. Baxter, T. L. Khoo, M. E. Bleich, M. P. Carpenter, I. Ahmad, R. V. F. Janssens, E. F. Moore, I. G. Bearden, J. R. Beene, and I. Y. Lee
Proceedings of the International Conference on Nuclear Structure at High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL-10613, Vol. 2, p. 370 (1992)

The Argonne Silicon Strip-Detector Array
A. H. Wuosmaa, B. B. Back, I. G. Bearden, R. R. Betts, M. Freer, J. Gehring, B. G. Glagola, T. Happ, D. J. Henderson, and P. Wilt
Proceedings of the International Conference on Nuclear Structure of High Angular Momentum and Workshop on Large Gamma-Ray Detector Arrays, Ottawa, Canada, May 18-21 and Chalk River, Canada, May 22-23, 1992, AECL- 10613, Vol. 2, p. 418 (1992)

Symmetries in Confined Classical Coulomb Systems
John P. Schiffer
Group Theory and Special Symmetries in Nuclear Physics, Proceedings of the International Symposium in Honor of K. T. Hecht, Ann Arbor, Michigan, 19-21 September, 1991, Edited by J. P. Draayer and J. Jänecke, (World Scientific, Singapore 1992), pp. 370-374

First Results from the Fragment Mass Analyzer at ATLAS
C. N. Davids, I. Ahmad, B. B. Back, I. G. Bearden, R. R. Betts, K. Bindra, C. R. Bingham, D. J. Blumenthal, R. Broda, M. P. Carpenter, P. Chowdhury, W. Chung, B. Crowell, P. J. Daly, B. Fornal, S. J. Freeman, M. Freer, J. Gehring, Z. W. Grabowski, D. J. Henderson, R. Henry, R. V. F. Janssens, T. Lauritsen, Y. Liang, C. J. Lister, R. H. Mayer, D. M. Moltz, D. Nisius, A. V. Ramayya, J. D. Robertson, F. Scarlassara, P. Spolaore, F. Soramel, and W. B. Walters
Proceedings of the 6th International Conference of Nuclei Far from Stability, and 9th International Conference on Atomic Masses and Fundamental Constants, Bernkastel-Kues, Germany, 19-24 July, 1992, p. PH8

Investigation of Proton Inelastic Scattering on ^{56}Ni in Inverse Kinematics
G. Kraus, P. Egelhof, C. Fischer, H. Geissel, A. Himmler, F. Nickel, G. Muenzenberg, W. Schwab, A. Weiss, J. Friese, A. Gillitzer, H. J. Koerner, M. Peter, W. Henning, J. P. Schiffer, J. V. Kratz, L. Chulkov, M. Golovkov, and A. Ogloblin
Proceedings of the 6th International Conference of Nuclei Far from Stability, and 9th International Conference on Atomic Masses and Fundamental Constants, Bernkastel-Kues, Germany, 19-24 July, 1992, p. PH14

Investigation of Proton-Rich Platinum and Mercury Isotopes with the Fragment Mass Analyzer at ATLAS and the Isotope Separator at UNISOR
K. S. Toth, C. N. Davids, Y. A. Akovali, B. B. Back, K. Bindra, C. R. Bingham, H. K. Carter, W. Chung, Y. Hatsukawa, D. J. Henderson, T. Lauritsen, P. F. Mantica, D. M. Moltz, A. V. Ramayya, J. D. Robertson, and W. B. Walters
Proceedings of the 6th International Conference of Nuclei Far from Stability, and 9th International Conference on Atomic Masses and Fundamental Constants, Bernkastel-Kues, Germany, 19-24 July, 1992, p. E18

Evidence for Alpha-particle Chain Configuration in ^{24}Mg
A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, B. G. Glagola, T. Happ,D. J. Henderson, P. Wilt, and I. G. Bearden
Proceedings of the 1992 International Nuclear Physics Conference, Wiesbaden, Germany, July 26-August 1, 1992, Vol. 2, p. 1.4.43

ATLAS DEVELOPMENT AND OPERATION

Status of the Uranium Upgrade of ATLAS
L. M. Bollinger, P. J. Billquist, J. M. Bogaty, B. E. Clifft, P. Markovich, F. H. Munson, R. C. Pardo, K. W. Shepard, and G. P. Zinkann
Proceedings of the IEEE Particle Accelerator Conference, 6-9 May 1991, San Francisco, CA, Accelerator Science and Technology, 91CH3038-7, Vol. 5, pp. 2987-2989 (1992)

First Operation of ATLAS Using the PII Linac and a Comparison to Tandem Injection
R. C. Pardo, L. M. Bollinger, P. J. Billquist, J. M. Bogaty, B. E. Clifft, P. Markovich, F. H. Munson, K. W. Shepard, and G. P. Zinkann
Proceedings of the Symposium of North Eastern Accelerator Personnel, 16-19 October 1991, Santa Fe, New Mexico, eds. J. Benson, L. Rowton, J. Tesmer, and R. Darling (World Scientific, Singapore), ISBN 981-02-1108-2, p. 51 (1992)

Status Report on the Positive Ion Injector (PII) for ATLAS at Argonne National Laboratory
G. P. Zinkann, N. Added, P. Billquist, J. Bogaty, B. Clifft, P. Markovich, D. Phillips, P. Strickhorn, and K. W. Shepard
Proceedings of the Symposium of North Eastern Accelerator Personnel, 16-19 October 1991, Santa Fe, New Mexico, eds. J. Benson, L. Rowton, J. Tesmer, and R. Darling (World Scientific, Singapore), ISBN 981-02-1108-?. p. 37 (1992)

Review of Superconducting Ion Linacs
L. M. Bollinger
Proceedings of the 1992 Linear Accelerator Conference, 24-28 August 1992, Ottawa, Ontario, AECL-10728, p. 13 (1992)

First Operating Results of the ATLAS Positive-Ion Injector
R. C. Pardo, P. J. Billquist, J. M. Bogaty, L. M. Bollinger, B. E. Clifft, F. H. Munson, K. W. Shepard, and G. Zinkann
Proceedings of the 1992 Linear Accelerator Conference, 24-28 August 1992, Ottawa, Ontario, AECL-10728, p. 70 (1992)

Upgraded Phase Control System for Superconducting Low-Velocity Accelerating Structures
N. Added, B. E. Clifft, and K. W. Shepard
Proceedings of the 1992 Linear Accelerator Conference, 24-28 August 1992, Ottawa, Ontario, AECL-10728, p. 181 (1992)

Coupled Superconducting Resonant Cavities for a Heavy-Ion Linac
K. W. Shepard and A. Roy
Proceedings of the 1992 Linear Accelerator Conference, 24-28 August 1992, Ottawa, Ontario, AECL-10728, p. 425 (1992)

Design for a Superconducting Niobium RFQ Structure
K. W. Shepard, W. L. Kennedy, and L. Sagalovsky
Proceedings of the 1992 Linear Accelerator Conference, 24-28 August 1992, Ottawa, Ontario, AECL-10728, p. 441 (1992)

MEDIUM-ENERGY PHYSICS

Saturation of Shadowing at Very Low Bjorken x
M. R. Adams and FNAL E665 Collaboration
Phys. Rev. Lett. 68, 3266-3269 (1992)

Measurement of Particle Production in Proton-Induced Reactions at 14.6 GeV/c
T. Abbott et al., and E-802 Collaboration
Phys. Rev. D 45, 3906-3920 (1992)

Global Transverse Energy Distributions in Relativistic Nuclear Collisions at 14.6 *A* 9GeV/c
T. Abbott et al., and E-802 Collaboration
Phys. Rev. C 45, 2933-2951 (1992)

Centrality Dependence of K^+ and π^+ Multiplicities from Si+*A* Collisions at 14.6 *A* GeV/*c*
T. Abbott et al., and E-802 Collaboration
Phys. Lett. B 291, 341-346 (1992)

First Measurement of Jet Production Rates in Deep-Inelastic Lepton-Proton Scattering
M. R. Adams and FNAL E665 Collaboration
Phys. Rev. Lett. 69, 1026 (1992)

Evidence Against a 17-keV Neutrino from ^{35}S Beta Decay
J. L. Mortara, I. Ahmad, K. P. Coulter, S. J. Freedman, B. K. Fujikawa, J. P. Greene, J. P. Schiffer, W. H. Trzaska, and A. R. Zeuli
Phys. Rev. Lett. 70, 394-397 (1992)

Shadowing in the Muon-Xenon Inelastic Scattering Cross Section at 490 GeV
M. R. Adams and FNAL E665 Collaboration
Phys. Lett. B 287, 375 (1992)

Photon-Hadron Interactions Revisited in Deep-Inelastic Muon Scattering
D. F. Geesaman
Z. Phys. C 56, S159 (1992)

Intermediate Mass Fragment Emission in Fe + Au Collisions
T. C. Sangster, H. C. Britt, D. J. Fields, L. F. Hansen, R. G. Lanier, M. N. Namboodiri, B. A. Remington, M. L. Webb, M. Begemann-Blaich, T. Blaich, M. M. Fowler, J. B. Wilhelmy, Y. D. Chan, A. Dacal, A. Harmon, J. Pouliot, R. G. Stokstad, S. Kaufman, F. Videbaek, Z. Fraenkel, G. Peilert, H. Stöcker, W. Greiner, A. Botvina, and I. N. Mishustin
Phys. Rev. C 46, 1405-1415 (1992)

$^3\vec{He}(\vec{e},e')$ Quasielastic Asymmetry
C. E. Jones, E. J. Beise, J. E. Belz, R. W. Carr, B. W. Filippone, W. Lorenzon, R. D. McKeown, B. A. Mueller, T. G. O'Neill, G. W. Dodson, K. Down, M. Farkhondeh, S. Kowslski, K. Lee, N. Makins, R. Milner, A. Thompson, D. Tieger, J. F. J. van den Brand, A. Young, X. Yu, and D. Zumbro
Phys. Rev. C 47, 110-130 (1992)

Measurement of Spin Observables Using a Storage Ring with Polarized Beam and Polarized Internal Gas Target
K. Lee, M. A. Miller, A. Smith, J.-O. Hansen, C. Bloch, J. F. J. van den Brand, H. J. Bulten, R. Ent, C. D. Goodman, W. W. Jacobs, C. E. Jones, W. Korsch, M. Leuschner, W. Lorenzon, D. Marchlenski, H. O. M T. Rinckel, J. Sowinski, F. Sperisen, E. Sugarbaker, C. Tschalär, O. Unal, and Z.-L. Zhou
Phys. Rev. Lett. 70, 738-741 (1993)

High Field Optical-Pumping Spin-Exchange Polarized Deuterium Source
A. Zghiche, K. P. Coulter, R. J. Holt, E. R. Kinney, R. S. Kowalczyk, D. H. Potterveld, D. K. Toporkov, L. Young, and B. Zeidman
Proceedings of the Workshop on Polarized Gas Targets for Storage Rings, Heidelberg, Germany, 23-26 September 1991, eds. H. G. Gaul, E. Steffens and K. Zapfe (Max-Planck-Institute, Heidelberg Report, April 1992) pp. 103-108

Depolarization of Atomic Targets by Beam-Induced Magnetic Fields
Edward R. Kinney
Proceedings of the Workshop on Polarized Gas Targets for Storage Rings, Heidelberg, Germany, 23-26 September 1991, eds. H. G. Gaul, E. Steffens and K. Zapfe (Max-Planck-Institute, Heidelberg Report, April 1992) pp. 155-158

Fission from Fe and Nb Reactions with Heavy Targets at 50-100 MeV/A
M. Begemann-Blaich, T. Blaich, M. M. Fowler, J. B. Wilhelmy, H. C. Britt, D. J. Fields, L. F. Hansen, R. G. Lanier, D. J. Massoletti, M. N. Namboodiri, B. A. Remington, T. C. Sangster, G. L. Struble, M. L. Webb, Y. D. Chan, A. Dacal, A. Harmon, J. Pouliot, R. G. Stokstad, S. Kaufman, F. Videbaek, and Z. Fraenkel
Phys. Rev. C 45, 677-688 (1992)

THEORETICAL PHYSICS

Color Transparency and High Energy (p,2p) Nuclear Reactions
T.-S. H. Lee and G. A. Miller
Phys. Rev. C 45, 1863-1870 (1992)

Null-Plane Dynamics of Particles and Fields
F. Coester
Progress in Particle and Nuclear Physics, ed. A. Faessler (Pergamon Press, Great Britain 1992) Vol. 29, pp. 1-32

Effects of Δ-Isobar Degrees of Freedom on Low-Energy Electroweak Transitions in Few-Body Nuclei
R. Schiavilla, R. B. Wiringa, V. R. Pandharipande, and J. Carlson
Phys. Rev. C 45, 2628-2639 (1992)

The Fermion Dynamic Symmetry Model and Superdeformation Near A=220
R. R. Chasman
Phys. Lett. B 280, 187-190 (1992)

Soft Dipole Excitations in ^{11}Li
H. Esbensen and G. F. Bertsch
Nucl. Phys. A542, 310-340 (1992)

Singularity Structure of a Model Quark Propagator
Conrad J. Burden, Craig D. Roberts, and Anthony G. Williams
Phys. Lett. B 285, 347-353 (1992)

Correlation Effects in $^{11}B(\pi^-,\pi^+)^{11}Li$ Reactions
H. Esbensen, D. Kurath and T.-S. H. Lee
Phys. Lett. B 287, 289-292 (1992)

Euclidean Proton Response in Light Nuclei
J. Carlson and R. Schiavilla
Phys. Rev. Lett. 68, 3682-3685 (1992)

Comment on "Scalar Aharonov-Bohm Effect with Neutrons"
Murray Peshkin
Phys. Rev. Lett. 69, 2017 (1992)

Elastic Scattering and Fusion Calculations for $^{16}O + {}^{63,65}Cu$
S. H. Fricke, H. Esbensen, and S. Landowne
Phys. Rev. C 45, 2500 (1992)

Photon Polarization Tensor and Gauge Dependence in Three-Dimensional Quantum Electrodynamics
Conrad J. Burden, Justin Praschifka, and Craig D. Roberts
Phys. Rev. D 46, 2695-2702

Fragmentation Reactions of ^{11}Li
H. Esbensen and G. F. Bertsch
Phys. Rev. C 46, 1552-1554 (1992)

Variational Calculation of the Ground State of ^{16}O
Steven C. Pieper, R. B. Wiringa, and V. R. Pandharipande
Phys. Rev. C 46, 1741-1756 (1992)

Two Loop Calculation of the ω-ρ Mass Splitting
Lloyd C. L. Hollenberg, Craig D. Roberts, and Bruce H. J. McKellar
Phys. Rev. C 46, 2057-2065 (1992)

Pion Absorption on Polarized Nuclear Targets
Mohammad G. Khayat, N. S. Chant, P. G. Roos, and T.-S. H. Lee
Phys. Rev. C 46 2415-2429 (1992)

On the Implications of Confinement
G. Krein, C. D. Roberts, and A. G. Williams
Intl. J. of Modern Phys. A 22, 5606-5624 (1992)

Chiral Symmetry and Threshold π^0 Electroproduction
Véronique Bernard, Norbert Kaiser, T.-S. H. Lee, and Ulf-G. Meissner
Phys. Rev. Letts. 70, 387-390 (1993)

Variational Monte Carlo Studies of Electromagnetic Structure of Few-Body Nuclei
R. Schiavilla
Proceedings of the Workshop on Monte Carlo Methods in Theoretical Physics, Marciana Marina, Elba Island, Italy, 27 June-6 July 1990, eds. Sergio Caracciola and Adelchi Fabrocini (ETS Editrice Pisa 1991) pp. 317-324

Variational Monte Carlo Calculations of Nuclear Ground States
R. B. Wiringa
Proceedings of the Workshop on Monte Carlo Methods in Theoretical Physics, Marciana Marina, Elba Island, Italy, 27 June-6 July 1990, eds. Sergio Caracciola and Adelchi Fabrocini (ETS Editrice Pisa 1991) pp. 325-333

Photodisintegration of the Deuteron at Medium and High Energies
T.-S. H. Lee
Proceedings of the 5th Workshop on Perspectives in Nuclear Physics at Intermediate Energies, ICTP, Trieste, Italy, 6-10 May 1991, eds. Sigfrido Boffi, Claudio Ciofi degli Atti, Mauro Giannini (World Scientific, Singapore 1992) pp. 318-324

Correlated Dipole Response of Neutron Rich Nuclei
Henning Esbensen
Proceedings of International Symposium on Structure and Reactions of Unstable Nuclei, 17-19 June 1991, Niigata, Japan, eds. K. Ikeda and Y. Suzuki, (World Scientific, Singapore 1991) pp. 178-186

Variational Monte Carlo Calculations of Finite Nuclei
R. B. Wiringa
Proceedings of the Seventh Internatioinal Conference on Recent Progress in Many-Body Theories,, 28-31 August 1991, Minneapolis, MN, eds. T. L. Ainsworth, C. E. Campbell, B. E. Clements, E. Krotscheck, (Plenum Press, NY 1992) Vol. 3 pp. 39-48

Front-Form Calculation of $\gamma d \rightarrow np$ Reactions at High Energies
T.-S. H. Lee
Proceedings of the XIIIth European Conference on Few-Body Problems in Physics, Marciana Marina, Isola d'Elba, Italy, 9-14 September 1991, eds. C. Ciofi degli Atti, E. Pace, G. Salmè, and S. Simula (Springer-Verlag, Wien 1992) Few-Body Systems, Supplementum 6, pp. 526-531

Effects of Δ-Isobar Degrees of Freedom on the Reactions $^3He(n,\gamma)^4He$ and $^3He(p,e^+\nu_e)^4He$ at Low-Energy
R. Schiavilla
in Perspectives on Theoretical Nuclear Physics, Proceedings of the IV Convegno su Problemi di Fisica Nucleare Teorica, Marciana Marina, 16-18 October 1991, eds. L. Bracci, P. Christillin, A. Fabrocini, S. Fantoni, G. Fiorentini, A. Kievsky, M. Rosa-Clot, S. Rosati, M. Viviani (ETS Editrice Pisa 1992) pp. 123-132

Theoretical Description of Electromagnetic Pion Production
T.-S. H. Lee
Poceedings of the Seventh Amsterdam Mini-Conference on Electromagnetic Production of Mesons on Nucleons and Nuclei, 12-13 December 1991, Amsterdam, The Netherlands, eds. H. P. Blok, J. H. Koch, and H. de Vries (Centrum voor Wiskunde en Informatica, Amsterdam 1992) pp. 1-21

Monte Carlo Calculations of Few-body and Light Nuclei
R. B. Wiringa
Proceedings of the Thirteenth International Conference on Few Body Problems in Physics, Adelaide, South Australia, 5-11 January 1992, eds. I. R. Afnan and R. Cahill, (Elsevier Science Publishers, B.V. 1992); Nucl. Phys. A543, 199c-212c (1992)

Few Body XIII "Conference Summary": Impressions of a Spectator
F. Coester
Proceedings of the Thirteenth International Conference on Few Body Problems in Physics, Adelaide, South Australia, 5-11 January 1992, eds. I. R. Afnan and R. Cahill, (Elsevier Science Publishers, B.V. 1992); Nucl. Phys. A543, 427c-434c (1992)

ATOMIC AND MOLECULAR PHYSICS

Collision Spectroscopy of Low-Energy U^{5+} Beam Ions,
D. A. Church, M. Druetta, R. W. Dunford, C.-J. Liu, C. Froese-Fischer, M. Indrees, and V. M. Umar
J. Opt. Soc. Am. B9, 2159 (1992)

Quantitative Molecular Spectroscopy using Coulomb Explosions
D. Zajfman, E. P. Kanter, T. Graber, Z. Vager, and R. Naaman
Nucl. Instrum. Methods B67, 22-25 (1992)

Influence of Multiple Scattering on the Coulomb-Explosion Imaging of Fast Molecules
D. Zajfman, T. Graber, E. P. Kanter, and Z. Vager
Phys. Rev. A46, 194 (1992)

A Source of Cold Molecular Ions for Coulomb-Explosion Imaging
T. Graber, D. Zajfman, E. P. Kanter, R. Naaman, Z. Vager, and B. J. Zabransky
ev. Sci. Instruments 63, 3569 (1992)

Laser-rf Double-Resonance Measurements of the Hyperfine Structure in ^{49}Ti II
N. Berrah-Mansour, C. Kurtz, L. Young, D. A. Beck, and D. Datta
Physical Review A46, 5774 (1992)

Spin-Exchange Optical Pumping as a Source of Spin-Polarized Deuterium
K. P. Coulter, R. J. Holt, E. R. Kinney, R. S. Kowalczyk, D. H. Potterveld, L. Young, B. Zeidman, A. Zgiche, and D. K. Toporkov
Physical Review Letters 68, 174 (1992)

Measurement of the 6p $^2P_{3/2}$ State Lifetime in Atomic Cesium
C. E. Tanner, A. E. Livingston, R. J. Rafac, F. G. Serpa, K. W. Kukla, H. G. Berry, L. Young, and C. A. Kurtz
Physical Review Letters 69, 2765 (1992)

Overview of Laser-Radiofrequency Double-Resonance Studies of Atomic, Molecular and Ionic Beams
W. J. Childs
Physics Reports 211, 114 (1992)

Use of Atomic-Beam Laser Radio-Frequency Double Resonance for Interpretation of Complex Spectra
W. J. Childs
J. Opt. Soc Am. B9, 191 (1992)

Comparisons of the QED/Relativistic Parts of the Triplet State Energies in the Helium-Like Sequence
H. G. Berry, R. W. Dunford, and A. E. Livingston
Phys. Rev. A 47, 698 (1993)

Branching Ratio for the M1 Decay of the 2 $^2S_{1/2}$ State in One Electron Krypton
S. Cheng, R. W. Dunford, E. P. Kanter, H. G. Berry, D. S. Gemmell, B. J. Zabransky, A. E. Livingston, L. J. Curtis, J. Bailey, and J. A. Nolen, Jr.
Phys. Rev. A47, February (1993)

State-of-the-Art Resolution in VUV Photoelectron Spectrometry
M. O. Krause, C. D. Caldwell, S. B. Whitfield, S. J. Schaphorst, and Y. Azuma
Synchrotron Radiation News 5, 25 (1992)

Electron Transfer from H_2 and Ar to Stored Multiply-Charged Argon Ions Produced by Synchrotron Radiation
S. D. Kravis, D. A. Church, B. M. Johnson, M. Meron, K. W. Jones, J. C. Levin, I. A. Sellin, Y. Azuma, N. Berrah-Mansour, H. G. Berry, and M. Druetta
Phys. Rev. A45, 6379 (1992)

X-Ray, Soft X-Ray and VUV Beam-Position Monitor
B. A. Karlin, P. L. Cowan, and J. Woicik
Rev. Sci. Instrum. 63, 526-529 (1992)

A Suite of Fortran Programs for Calculating Perfect Crystal X-Ray Diffraction Performance for Arbitrary Cystals at Arbitrary Wavelengths
S. Brennan and P. L. Cowan
Rev. Sci. Instrum. 63, 850-853 (1992)

Backreflection X-Ray Standing Wave and Crystal Truncation Rods as Structure Probe for Epilayer-Substrate Systems
H. Hashizume, M. Sugiyama, T. Niwa, O. Sakata, and P. L. Cowan
Rev. Sci. Instrum. 63, 1142-1145 (1992)

X-Ray Standing Wave Measurement of the InP(110) Surface Relexation
J. C. Woicik, T. Kendelewicz, K. E. Miyano, P. L. Cowan, C. E. Bouldin, B. A. Karlin, P. Pianetta, and W. E. Spicer
Phys. Rev. Lett. 68, 341-344 (1992)

Extended X-Ray Absorption Fine-Structure and X-Ray Standing Wave Study of the Clean InP(110) Surface Relaxation
J. C. Woicik, T. Kendelewicz, K. E. Miyano, P. L. Cowan, M. Richter, B. A. Karlin, C. E. Bouldin, P. Pianetta, and W. E. Spicer
J. Vac. Sci. Technol. A 10, 2041-2045 (1992)

X-Ray Beam Position Monitor Using a Quadrant PIN Diode
S. H. Southworth and P. L. Cowan
Nucl. Instrum. Methods A 319, 51-55 (1992)

Emittance, Brilliance and Bandpass Issues Related to an Inclined Crystal Monochromator
A. T. Macrander, D. R. Haeffner, and P. L. Cowan
Soc. Photo-Optical Instrum. Eng., 1740, 2 (1992)

Scattering and Stopping of Swift Diatomic Molecules under Coulomb Explosion
P. Sigmund
Nucl. Instrum. Methods, B67, 11-16 (1992)

Scaling Laws Governing the Multiple Scattering of Diatomic Molecules under Coulomb Explosion
P. Sigmund
Phys. Rev. A. 46, 2596-2606 (1992)