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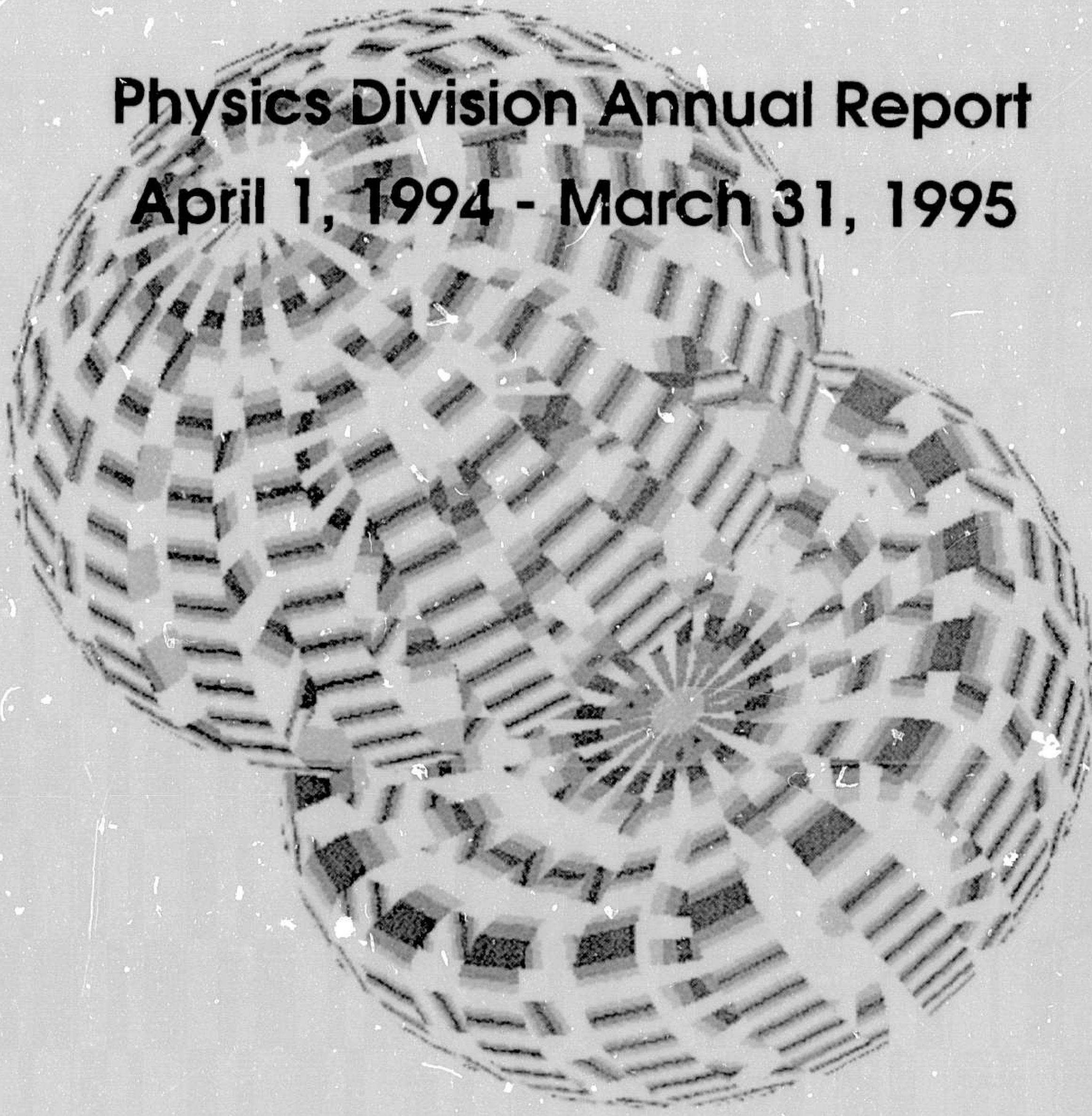
Physics Division Annual Report

April 1, 1994 - March 31, 1995



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PHYSICS DIVISION ANNUAL REPORT

April 1, 1994 -- March 31, 1995

Walter F. Henning
Director

August 1995

<u>Preceding Annual Reports</u>
ANL-92/16 1991-1992
ANL-93/12 1992-1993
ANL-94/31 1993-1994

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The cover depicts a constant-density ($\rho = 0.005\ fm^{-3}$) surface of a polarized deuteron in the $M = 1$ spin state, computed with the Argonne v_{18} potential. Using the Argonne IBM SP, similar structures were computed for $S = 1, T = 0$ pairs in ^4He and ^{16}O. (The visualization was suggested by Jun Forest, University of Illinois at Urbana-Champaign, and rendered by Steven C. Pieper using SPEAKEASY®.)

Edited by Karen J. Thayer

FOREWORD

This report summarizes the research performed over the past year by the Argonne Physics Division in the areas of nuclear and atomic physics. The Division's programs in nuclear physics include operation of ATLAS as a national heavy-ion user facility and related accelerator development, nuclear structure research and reactions with beams of heavy ions, primarily at ATLAS but also using forefront instrumentation elsewhere, medium energy nuclear physics at SLAC, Fermilab, Novosibirsk, DESY and CEBAF, and nuclear theory. In atomic and molecular physics the research programs are directed towards studies of highly charged ions at ATLAS, and towards studies with synchrotron radiation, currently at the National Synchrotron Light Source at Brookhaven but also in preparation for the future program at the Advanced Photon Source at Argonne.

At the FMA five new proton emitters were discovered this year, the heaviest known thus far. High-statistics measurements were performed with the APEX apparatus of electron-positron pairs emitted in close collisions of high-Z atoms at energies near the Coulomb barrier. The results appear to rule out the existence of sharp electron-positron lines previously reported elsewhere. New data on superdeformed bands shows evidence for the validity of the pseudo-spin coupling scheme and the observation of an unexpected small, but regular staggering in alternate energy levels suggesting the presence of a new symmetry. Considerable progress was made in addressing the long-standing problem of the decay from superdeformed bands by extracting the complete spectrum of gamma rays characterizing this decay and comparing it to calculations. These results also suggest that such decay spectra can probe the quenching of pairing as a function of temperature. The ^{18}F (p, α) reaction was measured at energies of astrophysical interest with a radioactive ^{18}F beam developed at ATLAS.

The ATLAS accelerator performed exceedingly well over the past year, providing 5200 hours of beam on target to the research program. A record number of 60 experiments were completed and facility reliability remained near the 90% level. Construction of a second, advanced ECR ion source for ATLAS was started. In accelerator development construction of a niobium superconducting RFQ structure is near completion. Prototyping of a new superconducting coupled-resonator structure is in progress in collaboration with the Nuclear Science Centre in New Delhi, India, for use with their future booster linac. The major emphasis in accelerator development was on plans for a future radioactive beam facility based on ATLAS. A working paper was prepared which presented the physics case, a novel concept for a 2-accelerator ISOL type facility based on ATLAS, and ongoing and future R&D projects relevant for such a facility.

In the Medium Energy Nuclear Physics program, research highlights include the first identification of diffractive deep inelastic scattering from nuclei observed in scattering of 490 GeV muons at Fermilab. This experiment also provides a clear signal for color transparency in the A-dependence of ρ-meson production, and of differences in the distributions of $\bar{u}$ and $\bar{d}$ quarks in nuclei. Major progress has been made in the construction of polarized hydrogen and deuterium targets via laser polarization, including a recent direct measurement of the nuclear polarization.

The Short Orbit Spectrometer (SOS) at CEBAF which was constructed under Argonne responsibility was completed and is presently being commissioned. Its operation in all of the first group of experiments at CEBAF, where the Argonne Medium Energy Physics program has a major presence, is scheduled for this year. A Cerenkov particle identification system built at Argonne was installed at the DESY laboratory in Hamburg in the HERMES experiment. HERMES, a study of the spin structure of the nucleon using the circulating positron beam in the HERA ring at DESY, began production running this year, and will produce the first high-statistics semi-inclusive spin measurements from deep-inelastic scattering.

In the Theory group the investigation of near threshold pion production in pp scattering has been extended to determine the πNN form factor from recent π^+ production data. The meson-exchange model developed over the past years has been successfully applied to investigate the electroproduction of pions on the three-nucleon systems, proton-proton bremsstrahlung, $pp \rightarrow \pi + d$ at high energies, and the effects of the Δ three-body force on effective interactions of the nuclear shell-model.

Progress was made in employing the Dyson-Schwinger equations as a semi-phenomenological tool for nonperturbative QCD. Important recent successes are the calculation of the electromagnetic pion form factor and of the $\gamma^* \pi^0 \rightarrow \gamma$ contribution to virtual Compton scattering. They demonstrate the unique ability of this approach to unify the perturbative and nonperturbative domains of QCD, where confinement and dynamical chiral-symmetry breaking are crucial.

A new nucleon-nucleon potential, Argonne v_{18}, was completed this year. It includes charge independence as the previous Argonne model, plus additional charge-dependent and charge-asymmetric terms. It provides an excellent fit to the latest pp and np elastic scattering data. Many-body calculations using this potential have been run on Argonne's new 128-processor IBM SP at speeds up to 7.5 GFLOPS. This has made possible calculations of A=6 nuclei, five-body cluster contributions to ^{16}O, and the first extensive studies of ^{40}Ca. The charge-independence breaking terms of the new Argonne v_{18} interaction allowed the study of the energy differences of mirror nuclei, i.e., the Nolen-Schiffer anomaly.

The Atomic Physics program focused on two principal areas: (1) accelerator-based atomic physics making use of highly charged heavy ions at ATLAS, (2) synchrotron-based atomic physics in preparation for the 7 GeV Advanced Photon Source (APS) at Argonne. The ATLAS-based program resulted in the development of a two-foil technique to measure ultrashort lifetimes in the 100 fs to 10 ps regime for highly-charged ions, the first measurement of the spectral distribution of the two-photon decay in helium-like systems, VUV spectroscopy in 3 to 5-electron systems to test *ab initio* atomic theories, and the interaction of highly charged ions with fullerenes.

The synchrotron-based atomic physics succeeded in verifying the dominance of Compton scattering in the x-ray region and its importance in recent measurements of the ratio of double-to-single photoionization of helium. Absorption spectroscopy was used to study atomic structure near the K-edge in alkalis and compare the results to relativistic Hartree-Fock calculations. The development of Raman spectroscopy as a structural tool was continued and its advantages for decomposition of complex features in an absorption spectrum were demonstrated. First measurements were performed using photon-electron coincidence techniques that will enable the detailed understanding of complex vacancy-decay mechanisms.

These are just a few of the highlights in the Division's research programs. The results, as always, reflect on the dedication of the Physics Division staff. This includes, in no small measure, the visitors and guests who participated in our research, as well as the more than 60 students from high school to graduate school.

Walter F. Henning

Walter F. Henning
Director, Physics Division

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I. HEAVY-ION NUCLEAR PHYSICS RESEARCH

The heavy ion research program in the Argonne Physics Division spans a broad range of activities from studies of superdeformed (SD) nuclei to the exploration of the limits of the valley of stability, from the characterization of reactions in the vicinity of the Coulomb barrier to the search for exotic new particles in collisions between very heavy nuclei, from the measurement of nuclear reactions of astrophysical interest to the development of a physics case and of a novel concept for the production and acceleration of exotic beams at ATLAS. This is a versatile program with involvement of many university groups and outside institutions, characterized by extensive collaborations between in-house and outside researchers. Most of these studies are carried out at the ATLAS accelerator, but parts of the program take advantage of forefront instrumentation elsewhere (in particular Gammasphere, Eurogam, and radioactive beams).

A major part of the research effort is devoted to γ-ray experiments with a focus on studies of superdeformation in the mass 150 and 190 regions. This research addresses the physics associated with states within the SD well and their coupling with states outside the well. Although states near the minimum of the SD well may lie high above the yrast line, they are cold since they are isolated from the hot normal states by a potential barrier.

We were the first to establish a new "island" of superdeformation in the mass 190 region a few years ago and since then in excess of 30 SD bands were found in this region. This large body of data was vital in identifying the occurrence of several pairs of "identical" bands. The identical bands, which were not anticipated, are still not explained, and may therefore imply a symmetry which has yet to be identified. To our recent discovery in ^{151}Dy of a SD band with transition energies midway between those in ^{152}Dy which provides additional evidence for the validity of the pseudospin coupling scheme, we can now add the unanticipated finding of a SD band in ^{154}Dy which has energies identical to those of an excited SD band in ^{153}Dy and is the first SD band found to decay to prolate collective normal states.

Another striking and unexpected observation is a small staggering in energy of alternate levels in three SD bands in ^{194}Hg, which suggests the presence in the collective Hamiltonian of a term invariant under a rotation by 90 degrees (C4 symmetry). The dipole transitions linking an excited SD band in ^{190}Hg to the yrast SD band were identified. This result reinforces the interpretation that the excited band corresponds to an octupole vibration. Two excited SD bands were observed in the doubly-magic ^{192}Hg nucleus.

We made considerable progress in addressing the long-standing problem of the decay from SD bands by using a novel approach. By extracting the complete spectrum of γ rays characterizing this decay in a number of mass 190 SD nuclei and comparing these data with calculations, we were able to propose that the decay spectra can probe the quenching of pairing with temperature.

With the advent of the new detector arrays, the emphasis of structure studies at ATLAS shifted towards nuclei that are difficult to investigate with conventional techniques or require the use of very heavy beams (Coulomb excitation). The combination of the Argonne Notre Dame BGO γ-ray facility with the Fragment Mass Analyzer (FMA) proved to be very successful. For example, the onset of deformation in the neutron-deficient Rn and Po isotopes was studied with mass identification.

A second major program that emerged recently is the study of exotic nuclei far away from the valley of beta stability and extending to very heavy elements. The excellent, high-intensity heavy ion beams from ATLAS and the high detection efficiency and excellent background suppression of the FMA provide unique new research opportunities ranging from proton radioactivity of heavy nuclei at the proton drip line to the production of isotopes of the heaviest elements and studies of their structure.

The separation of these products from background reactions is enormously improved with the recently installed recoil implantation system at the FMA. Nuclei identified according to their mass in the focal plane of the FMA are implanted in a Si-detector (segmented into 2304 pixels) located behind the focal-plane detector. This detector was instrumented recently with spectroscopy grade electronics. A subsequent alpha or proton decay at the implantation site, together with time-of-flight and recoil energy signals, reduced the background drastically so that cross sections at the nanobarn and sub-nanobarn levels can be measured. In this way, the heaviest proton-emitters known thus far were found: ^{167}Ir, ^{171}Au and ^{185}Bi. The beta decay of the N = Z nucleus ^{68}Se was also studied.

The implantation system also opens new opportunities for the study of very heavy nuclei. First experiments studying the alpha decays in the systems ^{58}Ni + ^{116}Sn (Z_{total} = 78), ^{92}Mo + ^{92}Mo (Z_{total} = 84), ^{64}Ni + ^{154}Sm (Z_{total} = 90), and ^{64}Ni + ^{181}Ta (Z_{total} = 101) were performed and an experiment with ^{48}Ca + ^{208}Pb (Z = 102) will take place soon.

The APEX project studies the effects of extremely strong electromagnetic fields in close collisions of high-Z atoms at energies close to the Coulomb barrier. This situation was predicted to give rise to qualitatively new phenomena associated with the over-critical binding of the inner electron orbits, such as the spontaneous emission of positrons.

Experiments originally motivated by these ideas, and carried out at GSI Darmstadt over the past decade, produced some remarkable and unusual results which, if confirmed, would seem to signal the appearance of some interesting and possibly fundamental new physics.

APEX - the ATLAS Positron Experiment - is a second-generation experiment, specifically designed to answer these questions. The apparatus was designed and constructed by a collaboration of scientists from Argonne, Chicago, Florida State, Michigan State, Princeton, Queen's, Rochester, Washington and Yale. The experiment features a high-acceptance, high-resolution detection system which, coupled with the high-intensity 100% duty factor beams from the recently upgraded ATLAS accelerator, allows data rates above those of the first-generation experiments and also allows, for the first time, a direct determination of the angles of emission of the positrons and electrons.

During the last year, APEX moved from the construction and testing phase to data production. Several highly successful runs were carried out studying e^+ - e^- production in U + Ta and U + Th collisions. The data sets for coincident lepton pairs are far greater than any of the published results. Many aspects of these data are still under analysis. However, at this stage the anomalous sharp sum-energy lines observed in earlier experiments were not seen.

Very recently, the intrinsic capabilities and the correct functioning of the APEX apparatus were demonstrated again in a measurement of the decay of the 3^- state in ^{206}Pb by internal pair conversion following ^{206}Pb + ^{206}Pb collisions. A peak at the expected energy was found in the positron-electron sum-energy spectrum.

Nuclear reactions at energies close to the barrier, where relative velocities between interacting nuclei are small, provide a unique regime for the study and understanding of the dynamics. We complemented our studies of the reaction channels in the systems ^{58,64}Ni + ^{92,100}Mo with fusion cross section measurements in the systems ^{58,64}Ni + ^{78,86}Kr. The degree of sub-barrier fusion enhancement can be understood by characterizing the structure of vibrational nuclei by their restoring force parameter C_2 which is calculated from the energy of the lowest 2^+ state and the associated B(E2) value. Nuclei with small C_2 values exhibit large sub-barrier enhancements while those with large C_2 values have smaller fusion yield.

Extremely deformed chain-like configurations of six α particles are suggested by calculations of the potential energy surface of ^{24}Mg as being sufficiently stable to be observable as resonances in the appropriate reaction channels. We continued our measurements for $^{12}C + ^{12}C$ inelastic scattering using a unique, highly segmented detector system of double-sided Si strip detectors. We conclusively identified the reaction $^{12}C(^{12}C,^{8}Be\ g.s.)^{16}O^*(4\alpha)$, where the recoiling ^{16}O decays into either two ^{8}Be nuclei or to $\alpha + ^{12}C(0_2^+)$. We observed discrete levels in ^{16}O populated at excitation energies near 17 and 19 MeV, in the same range of excitation energies where strong resonance behavior in $\alpha + ^{12}C$ scattering was interpreted as reflecting the population of elongated alpha-particle configurations in ^{16}O. We are also concentrating on the $^{12}C(^{12}C,^{12}C)^{12}C(3^-)$ channel in order to see if the large peak observed in the excitation function for the 3^--gs excitation at the same c.m. energy as the resonance in the inelastic $0_2^+ - 0_2^+$ channel also corresponds to these deformed configurations. A total angular momentum of 18 $\hbar^2$ for this channel was derived in a preliminary analysis.

In order to explore the influence of energy dissipation and mass flow on the dynamics of fission, we complemented earlier measurements of GDR γ rays with evaporation residue (ER) cross sections. As the host system cools down by emission of neutrons and charged particles, there is a finite chance to undergo fission after each evaporation step. If fission is suppressed due to dissipation, the enhanced survival probability will manifest itself by larger-than-expected ER cross sections. In the $^{32}S + ^{184}W$ system the ER cross sections show an increase with excitation energy, whereas a decrease is expected on the basis of statistical model calculations. The data indicate an increase in dissipation which is not understood.

Experiments in the area of astrophysics were performed with a ^{18}F beam, the first radioactive beam accelerated and used for reaction studies at ATLAS. A measurement of the $^{18}F(p,\alpha)$ reaction involved in the transition from the hot CNO cycle to the rp-process was successfully completed. We also explored the use of the FMA for radiative capture cross-section measurements of interest in astrophysics.

It is now widely recognized in the nuclear physics community that the acceleration of unstable beams opens up new research frontiers. To explore this new dimension, an extension of present technical capabilities and facilities is needed. Work towards the development of such a facility was undertaken in the Physics Division together with the community of scientists involved with ATLAS and others interested in this area of research. A working group is concentrating on the physics case for radioactive beams and on a novel technical concept for a facility with substantial capabilities incorporating ATLAS. An experiment exploring the production of neutron-rich isotopes with 100-MeV neutrons, 200-MeV deuterons and 200-MeV protons was performed in order to test some of the calculations that were done. A working document summarizing the current status of the discussions was prepared.

A. REACTION STUDIES

Reaction studies at ATLAS cover a range of topics including processes in the vicinity of the Coulomb Barrier, fusion and fission reactions at higher energies, and the production and decay of exotic nuclear cluster states in s-d shell nuclei. These studies take advantage of the characteristics of the ATLAS accelerator such as excellent beam quality, outstanding timing properties and easy energy variability. This research program utilizes a variety of detection systems such as the magnetic spectrographs, the fragment mass analyzer, and an array of double-sided silicon strip-detectors with the accompanying electronics.

Measurements performed this year continue to probe the factors governing the balance between quasielastic, fusion and deep inelastic reactions in this regime. For the first time, evidence was found for multi-neutron transfer reactions covering the full sequence from one-to six-neutron transfer in the system $^{58}Ni + {}^{100}Mo$. Attempts to understand the enhancement of sub-barrier fusion reactions involving nuclei with vibrational intrinsic structure in terms of the restoring force parameter C_2 were undertaken. This parameter can be calculated from the energy of the lowest 2^+ state and the associated B(E2) value. One observes that nuclei with small C_2 values exhibit a large sub-barrier enhancement, while nuclei with high values of C_2 show smaller fusion yields.

Experimental studies of the timescale of fission of hot nuclei were carried out recently using the emission rates of neutrons, gamma rays and charged particles as "clocks" for the fission process. These measurements showed that the fission process is strongly retarded (hindered) relative to expectations based on the statistical model of the process. A dynamical description appears to be more relevant and the experimental data are then expected to shed light on the dissipation in the shape degree of freedom. Rather than use the reactions mentioned above, we chose to measure the evaporation probability for hot nuclei in heavy-ion induced fusion reactions. As the hot system cools down by the emission of neutrons and charged particles, there is a finite chance to undergo fission after each evaporation step. If the fission branch is suppressed due to dissipation, there is therefore a strongly enhanced probability for survival which manifests itself as an evaporation residue cross section which is larger than expected from statistical model predictions. This effect depends only on the dissipation strength inside the saddle point and may provide the desired separation between pre-saddle and post-saddle dissipation. Experiments at ATLAS concentrated on the $^{32}S + {}^{184}W$, $^{100}Mo + {}^{116}Cd$ and $^{64}Ni + {}^{144,154}Sm$ systems.

Calculations of the potential energy surfaces of light nuclei suggest that extremely deformed configurations corresponding to linear chains of alpha particles might be sufficiently stable to be observable as resonances in the appropriate reaction channels. Over the last two years, we found evidence for a six-alpha chain in ^{24}Mg. Indeed, the excitation function for the $^{12}C(^{12}C,{}^{12}C(0_2^+))^{12}C(0_2^+)$ reaction shows a broad resonance that appears to correspond to a number of overlapping resonances with a rather particular relative phase. This was interpreted in theoretical work as corresponding to a degenerate band of overlapping states which might correspond to a new type of quantum state - a "deformation eigenstate". Last year we pursued our studies of these states by studying the four alpha-decaying states in ^{16}O as well as the $^{12}C(^{12}C,{}^{12}C)^{12}C(3^-)$ channel.

a.1. Observation of the One- to Six-Neutron Transfer Reactions at Sub-barrier Energies (C.-L. Jiang, K. E. Rehm, J. Gehring, B. Glagola, W. Kutschera, M. D. Rhein, and A. H. Wuosmaa)

It was suggested many years ago that when two heavy nuclei are in contact during a grazing collision, the transfer of several correlated neutron-pairs could occur. Despite considerable experimental effort, however, so far only cross sections for up to four-neutron transfers have been uniquely identified. The main difficulties in the study of multi-neutron transfer reactions are the small cross sections encountered at incident energies close to the barrier, and various experimental uncertainties which can complicate the analysis of these reactions. We have for the first time found evidence for multi-neutron transfer reactions covering the full sequence from one- to six-neutron transfer reactions at sub-barrier energies in the system ^{58}Ni + ^{100}Mo.

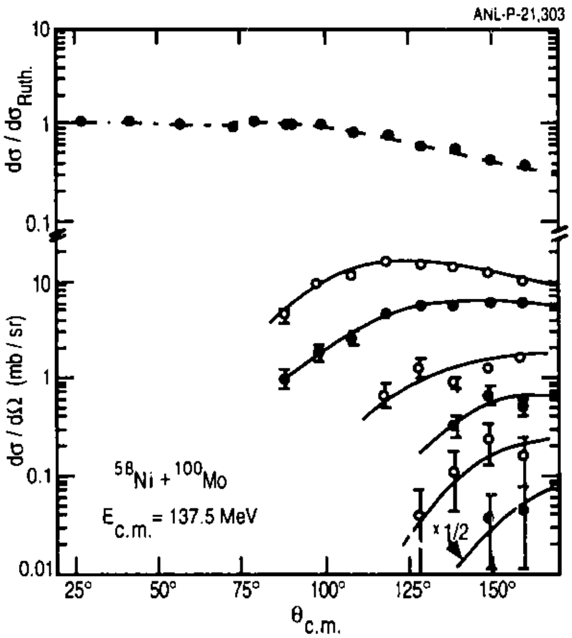

Fig. I-1. Angular distributions for elastic scattering (including inelastic excitations) and for the one- to six-neutron transfer reactions. The dashed line for the elastic scattering is the result of a coupled-channels calculation with the potential V = 79 MeV, r_0 = 1.19 fm, a = 0.63 fm, W = 40 MeV, r_i = 1.21 fm and a_i = 0.61 fm. The lines for the transfer reactions serve to guide the eye.

The experiment was performed in inverse kinematics with a 380-MeV ^{100}Mo beam bombarding a ^{58}Ni target. The scattered particles were analyzed according to their magnetic rigidity in a split-pole spect-rograph, and detected in a hybrid focal-plane detector. The mass and Z-resolutions were $A/\Delta A = 150$ and $Z/\Delta Z = 70$, respectively. The angular distributions for the one- to six-neutron transfer reactions which are all backward peaked with energy- and angle-integrated yields ranging from ~ 90 mb (1-n transfer) to 0.1 mb (6-n transfer) are shown in Figure I-1.

The centroids of the Q-values associated with the multi-neutron transfer reactions decrease with the number of transfer steps from about -1.5 MeV for the (^{58}Ni,^{59}Ni) reaction to about -25 MeV for the four- to six-neutron transfer channels. It is interesting to note that the time necessary to transferone particle, which is around 5×10^{-23} sec, corresponds to an energy uncertainty of about 13 MeV, in good agreement with the values observed in the experiment. Taking into account that the collision time [i.e. the time the two particles are in the region of the distance of closest approach (± 0.5 fm)] is ~ 36×10^{-23} sec, one notices that there is sufficient time for multiparticle transfer reactions to occur at these low bombarding energies.

The energy- and angle-integrated cross sections for the one- to six-neutron transfers show an exponential decrease with a reduction in cross section by a factor of 3.87 ± 0.17 for each transferred neutron. No enhancement of the energy-integrated cross sections for the 2n, 4n and 6n transfers with respect to the 1n, 3n and 5n yields is observed.

a.2. The Influence of Transfer Reactions on the Sub-Barrier Fusion Enhancement in the Systems ^{58,64}Ni + ^{,92,100}Mo (K. E. Rehm, C.-L. Jiang, H. Esbensen, J. Gehring, B. Glagola, W. Kutschera, Y. Liang, M. Rhein, K. Teh, F. L. H. Wolfs, and A. H. Wuosmaa)

High resolution experiments performed during the past few years demonstrated that the various reaction modes occurring in heavy ion collisions (e.g. elastic scattering, quasielastic and deep-inelastic reactions and fusion) can strongly influence each other. This interrelation of the different reaction modes brings a nuclear structure dependence to the fusion and deep-inelastic channels that were previously described in the framework of pure statistical models. In order to fully understand the interrelation between these reaction channels, a complete set of measurements including elastic and inelastic scattering, few-nucleon transfer and fusion is required.

In continuation of our earlier measurements of the fusion cross sections in the system ^{58,64}Ni + ^{92,100}Mo we finished the studies of the quasielastic process in these systems. The experiments were done in inverse reaction kinematics using the split-pole spectrograph with its hybrid focal-plane detector for particle identification. The experiments with ^{100}Mo beams were performed previously. First test runs with ^{92}Mo showed the possible interference with ^{98}Mo ions which could be eliminated by using the 13^+ charge state from the ECR source. The data from these experiments were completely analyzed. The smallest transfer cross sections are observed for the systems ^{64}Ni + ^{100}Mo and ^{58}Ni + ^{92}Mo, i.e., the most neutron-rich and neutron-deficient systems, respectively. For the other systems, ^{64}Ni + ^{92}Mo and ^{58}Ni + ^{100}Mo, the transfer cross sections at energies close to the barrier are about of equal magnitude. This observation does not correlate with the deviation of the experimental fusion cross sections from the coupled-channels predictions. While for ^{58}Ni + ^{100}Mo discrepancies between the experimental and theoretical fusion cross sections are observed, the system ^{64}Ni + ^{92}Mo which shows about the same transfer yields, is quite well described by the coupled-channels calculations.

a.3. Deep Inelastic Scattering Near the Coulomb Barrier (J. Gehring, B. Back, K. Chan,† M. Freer,‡ D. Henderson, C.-L. Jiang, K. E. Rehm, J. P. Schiffer, M. Wolanski, and A. Wuosmaa)

Deep inelastic scattering was recently observed in heavy ion reactions at incident energies near and below the Coulomb barrier. Traditional models of this process are based on frictional forces and are designed to predict the features of deep inelastic processes at energies above the barrier. They cannot be applied at energies below the barrier where the nuclear overlap is small and friction is negligible. The presence of deep inelastic scattering at these energies requires a different explanation.

The first observation of deep inelastic scattering near the barrier was in the systems ^{124,112}Sn + ^{58,64}Ni by Wolfs et al. We previously extended these measurements to the system ^{136}Xe + ^{64}Ni and currently measured the system ^{124}Xe + ^{58}Ni. We obtained better statistics, better mass and energy resolution, and more complete angular coverage in the Xe + Ni measurements. The cross sections and angular distributions are similar in all of the Sn + Ni and Xe + Ni systems. The data are currently being analyzed and compared with new theoretical calculations. They will be part of the thesis of J. Gehring.

†Yale University, ‡University of Birmingham, United Kingdom.

a.4. Measurements of Fusion Cross Sections in the Systems $^{58,64}Ni$ + $^{78,86}Kr$
(K. E. Rehm, C.-L. Jiang, H. Esbensen, B. Crowell, J. Gehring, B. Glagola, M. Rhein, and A. H. Wuosmaa)

We investigated the nuclear structure dependence of the sub-barrier fusion enhancement in heavy-ion induced reactions by studying the systems $^{58,64}Ni + ^{78,86}Kr$ at energies in the vicinity of the Coulomb barrier. These $^{78,86}Kr$ isotopes were selected because, similar to the Mo case discussed above, there are strong changes in nuclear structure as a function of the neutron number. However, contrary to Mo, where the "softness" of the nucleus increases with higher neutron number, the most collective nucleus for the Kr case is the neutron-deficient ^{78}Kr.

The experiment was performed with Kr beams from the positive-ion injector using enriched $^{78,86}Kr$ gas in the ECR ion source. The separation of evaporation residues from the elastically-scattered particles was achieved by using their difference in time-of-flight and magnetic rigidity in the gas-filled spectrograph.

The excitation functions for the four systems were compared to coupled-channels calculations including inelastic excitations of one- and two-phonon states in projectile and target. For systems involving ^{86}Kr, good agreement between theory and experiment is obtained, while for $^{78}Kr + ^{58,64}Ni$ an additional enhancement of the cross sections persisted at the lowest energies (see Figure I-2). It was found that this fusion enhancement correlates with the nuclear structure of the individual nucleus. Characterizing the structure of vibrational even-even nuclei by their restoring force parameter C_2, which can be calculated from the energy of the lowest 2^+ state and the associated B(E2) value, one observes that nuclei with small C_2 values exhibit a large sub-barrier fusion enhancement, while nuclei with high values of C_2 (usually closed-shell nuclei), show smaller fusion yields.

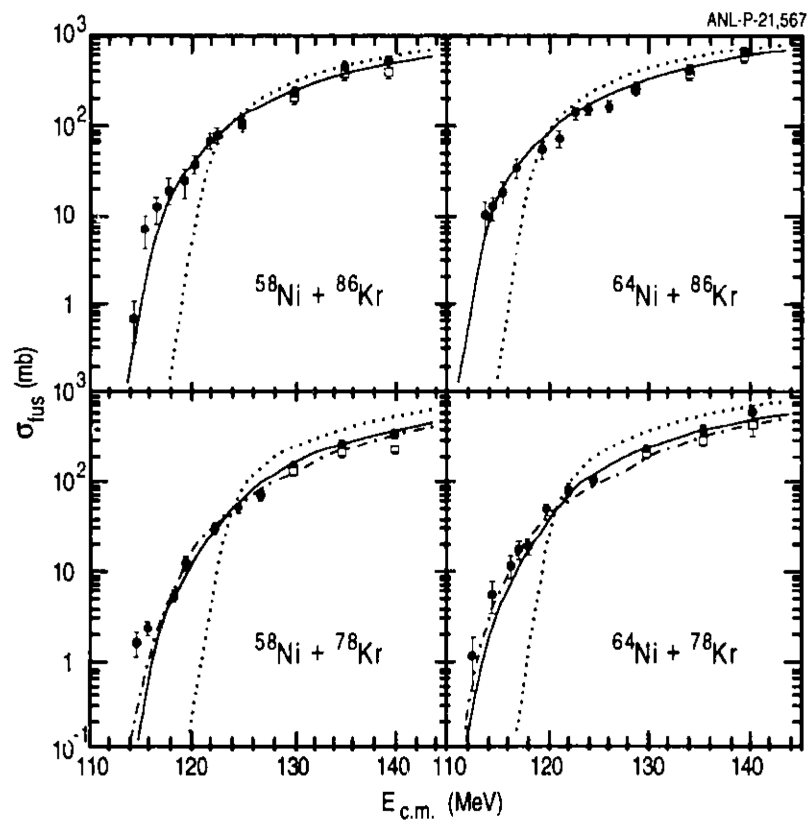

Fig. I-2. Fusion cross sections for the systems $^{58,64}Ni + ^{78,86}Kr$ (solid points) as function of the c.m. energy. The open squares represent the cross section for the evaporation residue production. The dotted lines are the result of one-dimensional barrier penetration calculations. The solid and dot-dashed lines are obtained by coupled-channels calculations performed in the rotating frame approximation.

a.5. Measurement of Fusion Excitation Functions in the System $^{78}Kr + ^{100}Mo$
(K. E. Rehm, C.-L. Jiang, H. Esbensen, B. Crowell, J. Gehring, B. Glagola, M. Rhein, and A. H. Wuosmaa)

Earlier measurements of fusion reactions involving ^{78}Kr and ^{100}Mo projectiles and Ni-targets showed surprisingly large fusion yields at low energies which could not be explained by coupled-channels calculations. The main difference to similar measurements involving the neighboring ^{86}Kr and ^{92}Mo isotopes was the different slope of the excitation functions at sub-barrier energies. An analysis of a variety of experiments showed a correlation between the nuclear structure and the slope of the excitation functions, with the "soft" transitional nuclei (^{78}Kr, ^{100}Mo) exhibiting shallower slopes than the "stiff" nuclei (^{86}Kr, ^{92}Mo) measured at the same energies with respect to the barrier. In this experiment we studied the fusion excitation function involving two transitional nuclei $^{78}Kr + ^{100}Mo$. The measurements were performed with ^{78}Kr beams from the ECR source at energies between 285-370 MeV. Separation of the evaporation nucleus from the elastically scattered particles was achieved by measuring time-of-flight and magnetic rigidity in the gas-filled spectrograph. The data were completely analyzed. A comparison of the cross sections with measurements for the system $^{86}Kr + ^{92}Mo$ populating the same compound nucleus ^{178}Pt is shown in Figure I-3. It shows good agreement at the highest energies, but quite different falloffs of the excitation functions toward lower energies. Coupled-channels calculations, including multi-phonon excitation for the two systems, are being performed.

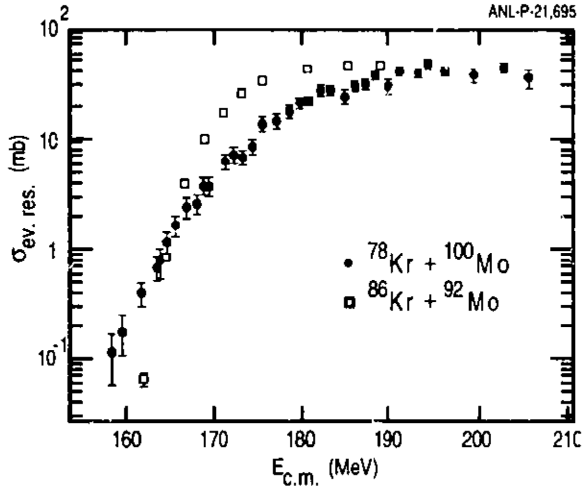

Fig. I-3. Comparison of the fusion cross sections for the systems $^{78}Kr + ^{100}Mo$ (solid points) and $^{86}Kr + ^{92}Mo$ (open squares) populating the same compound nucleus ^{178}Pt.

a.6. Fusion Excitation Functions Involving Transitional Nuclei
(K. E. Rehm, C.-L. Jiang, H. Esbensen, B. Crowell, J. Gehring, B. Glagola, M. Rhein,and A. H. Wuosmaa)

Measurements of fusion excitation functions involving transitional nuclei ^{78}Kr and ^{100}Mo showed a different behavior at low energies, if compared to measurements with ^{86}Kr and ^{92}Mo (see sections above). This points to a possible influence of nuclear structure on the fusion process.

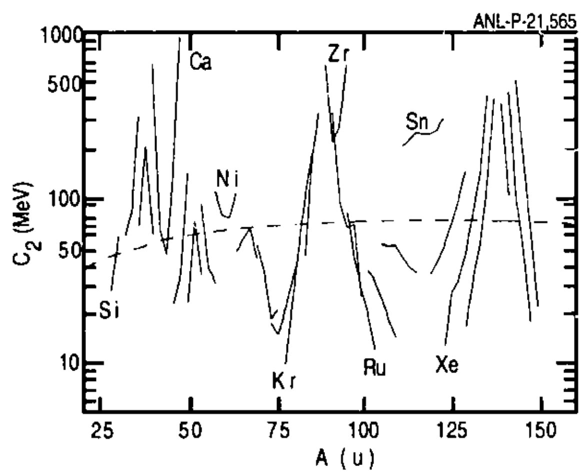

Fig. I-4. Restoring force parameter C_2 for stable even-even nuclei with masses between A = 28 and A = 150. C_2 values for isotopes of a given element are connected by solid lines. The dashed line is the prediction from the liquid-drop model.

One way to characterize the structure of vibrational nuclei is via their restoring force parameters C_2 which can be calculated from the energy of the lowest 2^+ state and the corresponding B(E2) value. A survey of the even-even nuclei between A = 28-150 shows strong variations in C_2 values spanning two orders of magnitude (see Figure I-4). The lowest values for C_2 are observed for ^{78}Kr, ^{104}Ru and ^{124}Xe followed by $^{74,76}Ge$, $^{74,76}Se$, ^{100}Mo and ^{110}Pd. In order to learn more about the influence of "softness" on the sub-barrier fusion enhancement, we measured cross sections for evaporation residue production for the systems $^{78}Kr + ^{104}Ru$ and $^{78}Kr + ^{76}Ge$ with the gas-filled magnet technique. For both systems, fusion excitation functions involving the closed neutron shell nucleus ^{86}Kr were measured previously. The data are presently being analyzed.

a.7. Evaporation Residue Cross Sections for $^{32}S + ^{184}W$ (B. B. Back, D. J. Blumenthal, C. N. Davids, D. J. Henderson, R. Hermann, D. J. Hofman, C.-L. Jiang, H. T. Penttilä, A. H. Wuosmaa, and P. Paul*)

We recently measured evaporation residue cross sections for the $^{32}S + ^{184}W$ system over a range of beam energies using the Argonne Fragment Mass Analyzer (FMA). Absolute cross sections were obtained on the basis of the recent determination of the transmission probability through the FMA of heavy, slow-moving reaction products.

The measurements were carried out using ^{32}S-beams from the ATLAS superconducting linac at Argonne. Beam energies of 165, 174, 185, 195, 205, 215, 225, 236, 246, and 257 MeV were used. The sliding-seal target chamber is used to allow for measurements at finite angles.

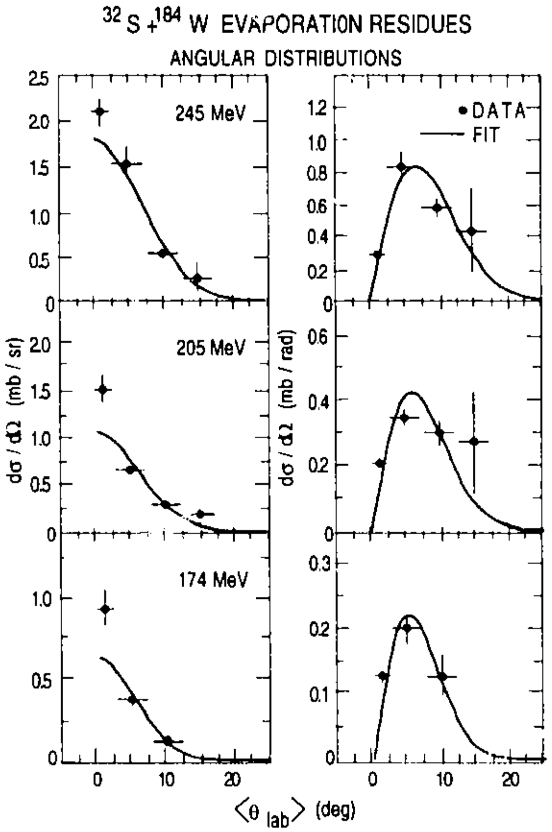

Fig. I-5. Angular distributions given in terms of (dσ/dΩ) and dσ/dθ are shown for three different beam energies in the left and right panel, respectively. The solid curves are Gaussians in the dσ/dΩ representation, which represent the best fit to the dσ/dθ data.

Evaporation residues were identified by time-of-flight and energy measurement using the focal-plane PPAC detector and the Si-strip detector placed ~ 40 cm behind the focal plane. A 40-μg/cm^2 carbon foil was placed in front of the FMA ~ 10 cm from the target in order to reset anomalous charge-state distributions arising from the decay of short-lived isomers.

The angular distributions of evaporation residues were measured at three beam energies utilizing the sliding-seal target chamber for the FMA. Differential cross sections converted to dσ/dθ, were integrated over angle to obtain the total evaporation residue cross section (see Fig. I-5). This was the first experiment which took advantage of the capability of the FMA to rotate off 0°.

The data obtained for the $^{32}S + ^{184}W$ system show an increasing evaporation cross section with excitation energy, whereas a decrease is expected on the basis of statistical model considerations and calculations. The data indicate an increase in the linear normalized dissipation coefficient γ from $\gamma = 0$ at $E_{exc} = 85$ MeV to $\gamma = 5$ at $E_{exc} = 135$ MeV (see Fig. I-6). This increase is not predicted nor understood within existing theoretical dissipation models and warrants further study, both experimentally and theoretically. This work is being prepared for publication.

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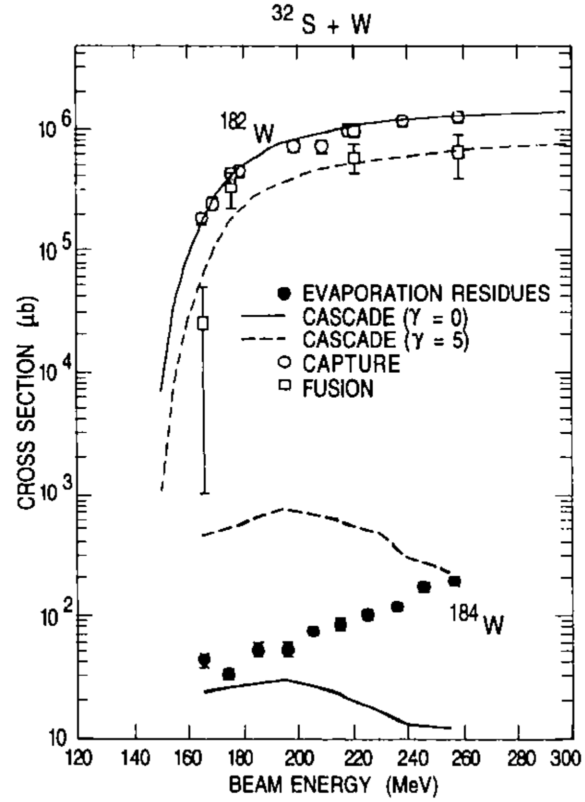

Fig. I-6. The measured evaporation residues for the $^{32}S + ^{184}W$ reaction (solid points) are compared with statistical model calculations using the CASCADE code with (p = 5) or without (γ + 0) nuclear dissipation. Complete fusion cross sections used in these calculations were obtained from extra push model calculations (thin dashed curve) which reproduce cross section estimates (open squares) obtained from fission angular distribution measurements.

a.8. Evaporation Residue Cross Sections for the $^{100}Mo + ^{116}Cd$ Reaction -- Energy Dissipation in Hot Nuclei (B. B. Back, D. J. Blumenthal, C. N. Davids, R. H. Hermann, D. J. Henderson, W. F. Henning, D. J. Hofman, H. T. Penttilä, and A. H. Wuosmaa)

In this experiment we tried to measure the evaporation residue cross section over a wide range of beam energies for the $^{100}Mo + ^{116}Cd$ reaction using the FMA. However, because of longer-than-estimated runs needed at each beam energy, and the difficulty of bending evaporation residues at the higher energies in the FMA, data were taken only at beam energies of E_{beam} = 460, 490, and 521 MeV, which correspond to excitation energies of E_{exc} = 62, 78, and 95 MeV, respectively.

By comparing to results for the $^{32}S + ^{184}W$ reactions measured recently, we expect to demonstrate a strong entrance channel effect related to the hindrance of complete fusion in near-symmetric heavy systems (a fusion hindrance factor of the order 7-10 is expected on the basis of the Extra-Push Model). The data are being analyzed.

a.9. Evaporation Residue Cross Sections for the $^{64}Ni + ^{144,154}Sm$ Reaction -- Energy Dissipation in Hot Nuclei (B. B. Back, D. J. Blumenthal, C. N. Davids, D. J. Henderson, W. F. Henning, and D. J. Hofman)

The fission hindrance of hot nuclei was deduced recently from an enhanced emission of GDR γ rays, neutrons and charged particles prior to scission of heavy nuclei. In the most recent experiments addressing this topic, namely new measurements of the pre-scission γ rays and evaporation residues from the $^{32}S + ^{184}W$ reaction, a rather sharp transition from negligible to full one-body dissipation occurs over the excitation energy region E_{exc} = 60-100 MeV. However, the cross section does not appear to level out or start to decline again at the upper end of the energy range as expected in this interpretation. It is therefore clearly desirable to extend the excitation energy range to look for such an effect in order to either corroborate or refute this interpretation.

The aim of this work is two-fold: 1) to study the fission hindrance in hot nuclei as a result of an increase in the dissipation strength with excitation energy and 2) to study the increased fusion hindrance expected for more mass symmetric entrance channel systems by comparing the measured evaporation residue cross sections to those obtained earlier using the $^{32}S + {}^{182}W$ reaction.

Preliminary estimates of the evaporation residue cross sections a[illegible] excitation energies for the $^{64}Ni + {}^{154}Sm$ reaction were obtained on the basis of measure[illegible] zero degrees in ATLAS experiment No. 460. These results cover the region from E_{exc} [illegible] 102 MeV corresponding to near-barrier beam energies. With the present work we plan to extend these measurements up to $E_{exc} \approx 250$ MeV and measure the angular distribution of evaporation residues for improved accuracy of the resulting cross sections. We plan also to re-measure at two of the energies measured earlier in order to obtain a better cross section estimate from those data.

The dynamical hindrance of complete fusion was predicted first by the Extra-Push model of Swiatecki and later confirmed by several other theoretical models which include a dissipation mechanism in connection with the mass re-arrangement in nuclear systems. The overall validity of these models was proven in measurements of evaporation residue cross sections, fission angular distributions etc. In attempts to understand the production cross sections of the heaviest elements Z = 107-111 it was suggested that the shell structure of the target may reduce the Extra Push energy required for fusion to take place.

To further test these ideas we plan to measure the fusion cross section for ^{64}Ni on $^{144,154}Sm$ targets. This would allow for a comparison between the spherical ^{144}Sm target and the strongly deformed ^{154}Sm target. It is believed that this direct comparison between two otherwise rather similar systems will enable us to isolate the possible effects of target shell closure at the N = 82 shell on the fusion probability.

The experiment will be carried out at the Fragment Mass Analyzer using the sliding-seal scattering chamber to allow for an angular distribution measurement. The measurement of the angular distributions for at least a few beam energies is necessary in order to obtain accurate cross sections and provide a reliable normalization of the earlier data. A square entrance aperture covering 4.5° × 4.5°, for which the FMA transport efficiency was measured, will be placed at the FMA entrance. A monitor detector with a well-defined angle and solid angle will be placed in the scattering chamber and used for the absolute cross section normalization.

The standard FMA focal plane PPAC will be used for the detection of evaporation residues in the focal plane. A 16 × 16 strip Si detector will be placed 40 cm downstream for time-of-flight and energy measurements in order to separate evaporation residues from scattered beam particles. This is relevant when measuring at 0°, where the beam is stopped on the first anode of the FMA. This setup is identical to the one for which the transport efficiency of the FMA was measured.

The ATLAS Program Advisory Committee has approved 4 days of beam time for this experiment.

a.10. Time Scale in Quasifission Reactions (B. B. Back, P. Paul,* J. Nestler,* K. S. Drese,* D. J. Hofman,* S. Schadmand,* and R. Varma*)

The quasifission process arises from the hindrance of the complete fusion process when heavy-ion beams are used. The strong dissipation in the system tends to prevent fusion and lead the system towards reseparation into two final products of similar mass reminiscent of a fission process. This dissipation slows down the mass transfer and shape transformation and allows for the emission of high energy γ-rays during the process, albeit with a low probability. Giant Dipole γ rays emitted during this time have a characteristic spectral shape and may thus be discerned in the presence of a background of γ rays emitted from the final fission-like fragments. Since the rate of GDR γ

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emission is very well established, the strength of this component may therefore be used to measure the timescale of the quasifission process. In this experiment we studied the reaction between 368-MeV ^{58}Ni and a ^{165}Ho target, where deep inelastic scattering and quasifission processes are dominant. Coincidences between fission fragments (detected in four position-sensitive avalanche detectors) and high energy γ rays (measured in a 10" × 10" actively shielded NaI detector) were registered. Beams were provided by the Stony Brook Superconducting Linac.

The γ-ray spectrum associated with deep inelastic scattering events is well reproduced by statistical cooling of projectile and target-like fragments with close to equal initial excitation energy sharing. The γ spectrum associated with quasifission events is well described by statistical emission from the fission fragments alone, with only weak evidence for GDR emission from the mono-nucleus. A 1σ limit of $t_{ss} < 11 \times 10^{-21}$ s is obtained for the mono-nucleus lifetime, which is consistent with the lifetime obtained from quasifission fragment angular distributions. A manuscript was accepted for publication.

a.11. Angular Correlation Measurements for $^{12}C^{12}C,^{12}C^{12}C$ 3^- Scattering
(A. H. Wuosmaa, R. R. Betts, M. Freer*)

Previous studies of inelastic $^{12}C + ^{12}C$ scattering to a variety of final states identified significant resonance behavior in a number of different reaction channels. These resonances can be interpreted as either potential scattering resonances, or as population of cluster structures in the compound nucleus ^{24}Mg, or as some interplay between the two mechanisms. Currently, for many of these resonances the situation remains unclear. One example is a large peak observed in the excitation function for the 3^- - g.s. excitation, identified in previous work performed at the Daresbury Laboratory in England.[1] This peak is observed at the same center-of-mass energy as one observed in the $0_2^+-0_2^+$ inelastic scattering channel.[2] That structure was suggested to correspond to exotic deformed configurations in the compound nucleus ^{24}Mg. As the peak in the 3^- + g.s. exit channel occurs at precisely the same energy as the purported resonance, it is tempting to associate the two. Before such an association can be confirmed or ruled out, further information must be obtained about the 3^- + g.s. structure. In particular, it is important to determine the angular momenta that dominate the 3^- + g.s. structure.

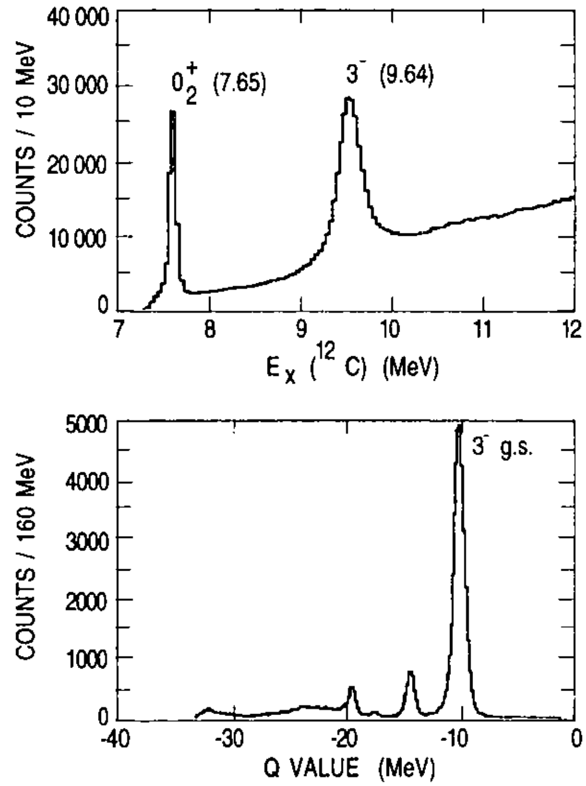

Fig. I-7. (a) ^{12}C excitation energy spectrum from 3 α particle coincidence events. (b) $^{12}C + ^{12}C$ inelastic scattering Q-value spectrum obtained at $E_{(c.m.)}$ = 33.5 MeV. The data are histogrammed for events in which three alpha particles arose from the decay of a ^{12}C nucleus in its 3^- state. The 3^- groundstate excitation is observed at Q = -9.64 MeV.

Extraction of resonance spins from inelastic scattering to final states with non-zero channel spins is usually impossible due to the washing out of the inelastic scattering angular distribution by the contribution of several magnetic substates. By measuring the angular correlations of the products

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[1]B. R. Fulton, T. M. Cormier, B. J. Hermann, Phys. Rev. C 21, 198-203 (1980).

[2]A. H. Wuosmaa et al.,. Phys. Rev. Lett. 68, 1295-1298 (1992).

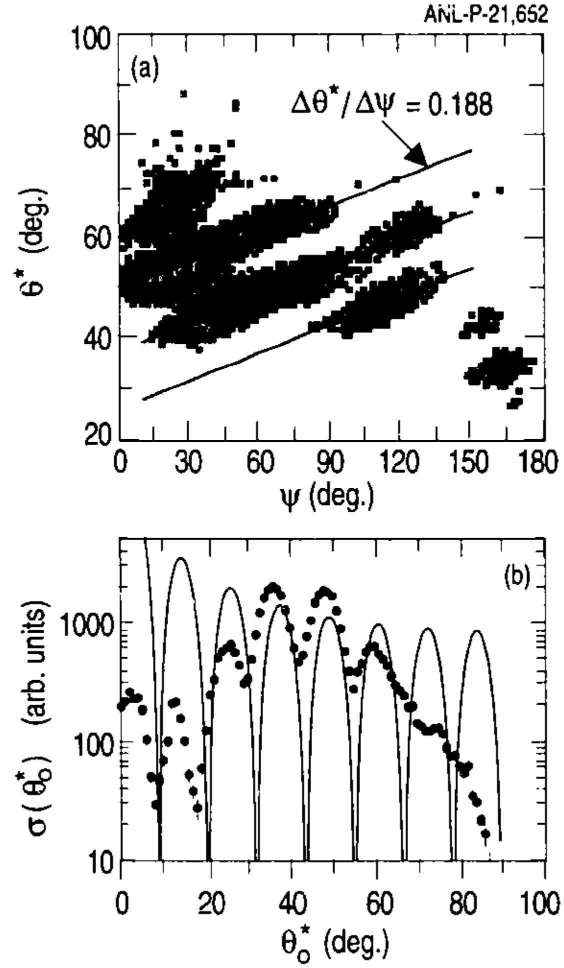

Fig. I-8. (a) Angular correlation matrix for $^{12}C(g.s.)+^{12}C(3^-)$ inelastic scattering at $E_{(c.m.)}$ 33.5 MeV. θ corresponds to the $^{12}C + ^{12}C$ center-of-mass scattering angle, and φ to the angle the relative α-^8Be velocity makes with the beam direction. (b) Projected angular correlation of the matrix in Figure I-7 onto the θ axis.*

of the decay of the excited level in ^{12}C, either by gamma rays or α particles, this complication can be overcome and the dominant orbital angular momenta in the scattering system can be determined. The 3^- level in ^{12}C at 9.64 MeV decays almost exclusively via α particle emission to the ground state of ^8Be, which subsequently decays into two additional α particles.

We studied these angular correlations in $^{12}C + ^{12}C$ inelastic scattering at several energies in the region of the excitation function peak for the 3^- + g.s. channel using an array of 4 double-sided silicon strip detectors. ^{12}C beams from the ATLAS accelerator bombarded 50-μg/cm^2 ^{12}C targets at seven energies between $E_{(beam)}$ = 52 and 76 MeV, in the region of strong non-statistical resonance-like behavior in the $^{12}C(g.s.) + ^{12}C(3^-)$ inelastic scattering channel. Any event in which at least three segments on any of the four strip detectors fired was recorded on tape. Excellent statistics for the 3^- + g.s. excitation were obtained at all energies (see Fig. I-7).

With these segmented detector devices, the three α particles from the decay of the excited ^{12}C nucleus are detected, and the ^{12}C scattering angle, the reaction Q value, and the angular correlation between the α-^8Be decay direction and the scattering angle of the excited ^{12}C can be determined. Figure I-7 illustrates a two-dimensional angular correlation matrix for the 3^- ground-state excitation, obtained at a beam energy of 67 MeV. The Y axis corresponds to the $^{12}C + ^{12}C$ center-of-mass scattering angle, and the X axis to the angle between the α-^8Be relative velocity and the beam direction. The pronounced ridges in the angular correlation contain information about both the substate population of the decaying $^{12}C(3^-)$ level, and the orbital angular momentum between the two ^{12}C nuclei.

Under simple approximations, a projection of the data along the ridges onto the Y axis should display sensitivity to the orbital angular momentum ℓ. Figure I-8 shows such a projection. In this representation the data are strongly oscillatory, with a periodicity consistent with $\ell \sim 15$. Assuming a fully aligned configuration, this ℓ value corresponds to a dominant resonance angular momentum of 18 $\hbar$. A fuller analysis of the magnetic substate populations extracted from these data can be used to verify the assumption of full alignment in this case. The results of this analysis should provide considerable additional information about the resonance angular momenta, and the reaction mechanisms at work in this scattering channel.

a.12. Angular Correlation Measurements for 4-α Decaying States in ^{16}O
(A. H. Wuosmaa, B. B. Back, R. R. Betts, D. J. Blumenthal, B. G. Glagola, D. J. Henderson, R. V. F. Janssens, D. Nisius, and M. D. Rhein)

Previous measurements of the $^{12}C(^{12}C,^{8}Be)^{16}O^*$ (4 α) reaction identified discrete levels in ^{16}O which decay by breakup into 4 α particles through a number of different decay sequences, including $^{16}O^* \rightarrow {}^{8}Be + {}^{8}Be$ and $\alpha + {}^{12}C\ (0_2^+)$.[1] These states are observed in a range of excitation energies where resonances are observed in inelastic $\alpha + {}^{12}C$ scattering leading to the $^{8}Be + {}^{8}Be$ and $\alpha + {}^{12}C\ (0_2^+)$ final states.[2,3] These resonances were associated with 4 α -particle chain configurations in ^{16}O. Should the states populated in the $^{12}C + {}^{12}C$ reaction possess this same extended structure, it would serve as an important piece of evidence supporting the idea that even more deformed structures are formed in the ^{24}Mg compound system. In order to more firmly make this association, it is important to determine the spins of the states populated in the $^{12}C + {}^{12}C$ reaction.

This determination can be made for states decaying to $\alpha + {}^{12}C\ (0^+)$ or $^{8}Be + {}^{8}Be$ since these decay fragments have zero spin. In this case, the angular correlations between the primary decay fragments can be used to determine these spins. In order to measure these correlations, we performed a measurement using 6 double-sided silicon strip detectors to detect the α particles from the decaying primary ^{8}Be, and the remaining α particles from the decaying ^{16}O. ^{12}C beams from ATLAS at three energies, 62, 65 and 67 MeV, were used to bombard 50-$\mu g/cm^2$ ^{12}C targets, and all events in which four or more hits were registered in the strip-detector array were recorded. The data are still at a very early stage of analysis. However, on-line indications are that the improved detector acceptance and longer run times at each energy will yield approximately an order of magnitude more data for the four α-particle decaying states than was obtained in the previous experiment. This measurement also marks the first use of the new Michigan State University data-acquisition system for non-APEX experiments at ATLAS.

[1]A. H. Wuosmaa, Z. Phys. A349, 249-253 (1994). [2]P. Chevallier et al., Phys. Rev. 160, 827-834 (1967). [3]L. L. Ames, Ph.D. Thesis, University of Wisconsin, Madison (1979).

B. GAMMA-RAY SPECTROSCOPY STUDIES

The major part of the work at Argonne concentrates on the study of superdeformation, primarily in the mass 190 region, but also in the mass 150 and 80 regions. Our work covers not only the nature of states inside the SD minimum, but also elucidates the physics related to the feeding into and decay from this minimum. There is also a diverse program on non-superdeformed nuclei, which covers aspects such as: quenching of pairing with temperature, a search for double octupole-phonon states in ^{208}Pb, conservation of the K-quantum number at high spin, phase transitions in mesoscopic systems, structure of high-lying states in actinide nuclei, spectroscopy of fission fragments, and structure of nuclei far from stability (conducted with the FMA).

New large γ-ray detector arrays are currently under construction in the United States (Gammasphere) (GS) and in Europe (Eurogam). These new arrays provide new opportunities for nuclear structure research. Argonne is participating vigorously in the construction of Gammasphere and performed experiments with the so-called "early implementation phase" of the device in 1993-1995. The group is also collaborating in several experiments at Eurogam. Results from these experiments show clearly the promise and power of these devices. At Argonne we developed a battery of programs to analyze the new high-fold data from these instruments.

The main research tool at ATLAS for this program is 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. Auxiliary equipment include: a scattering chamber, constructed by the University of Kansas, for coincidence measurements between γ rays and particles; a plunger apparatus, developed by the University of Notre Dame, for recoil-distance measurements of nuclear lifetimes; and dedicated chambers for special experiments (g-factor measurements, fission-fragment coincidence measurements, etc.). A rare capability exists at ATLAS for performing γ-γ coincidence experiments with the Fragment Mass Analyzer (FMA). This combination allows very weak reaction channels to be studied which would otherwise be impossible without mass tagging. Ten Compton-suppressed Ge spectrometers can be located at the target position of the FMA for this purpose. A support for up to 7 Compton-suppressed spectrometers at the magnetic spectrograph is also available.

Several projects are joint efforts with groups from Lawrence Berkeley and Lawrence Livermore Laboratories, the University of Notre Dame, Purdue University, North Carolina State University, INEL-Idaho National Engineering Laboratory, the Australian National University, the University of Manchester, the University of Tennessee, the University of Liverpool and Rutgers University. The work at Eurogam was performed in collaboration with several other European laboratories.

B.a. States in the Superdeformed Secondary Minimum and Their Coupling with States in the Normal Well

I. Introduction

The occurrence of an excited secondary minimum at large deformation provides a rare opportunity to study states which are cold, although highly excited with respect to the normal yrast line. Within the superdeformed well, isolated from normal states with smaller deformation, there is a cold "ground" state, as well as low-lying excited states that can give rise to sharp equally-spaced transitions. With increasing excitation energy, the coupling with states outside the well grows until the separate identity of SD states melts away; in addition, the collective properties may be altered. When the SD "yrast" state lies high enough above the true (normal) yrast state, then a coupling occurs between a cold system with a hot normal one, causing the SD band to decay.

Research on superdeformation at Argonne addresses the physics associated with states within the SD well and their coupling with states outside the well. Investigation of the decay out of SD states into lower-lying normal states allows us to examine the coupling between a cold, ordered system and a hot, chaotic one. In addition, it leads to the first experimental determinations of the spins and excitation energies of states in a SD minimum and, quite unexpectedly, a tool for investigating the reduction of pairing in a mesoscopic system. Discrete line spectroscopy investigates the cold SD bands. Study of the feeding of SD bands and of the associated quasicontinuum γ rays probes the nature of excited states and their increasing mixing with normal states.

II. Decay of SD Bands

We solved the long-standing problem of decay from SD bands by using a novel approach. Instead of trying to decipher the fragmented decay pathways, we instead measured the complete spectrum of γ rays decaying out of the SD band. We were able to characterize the *decay mechanism*, and define experimental *excitation energies and spins for a SD band* in ^{192}Hg. We have extracted the complete spectrum of the γ rays linking states in two separate wells in a number of mass 190 nuclei. The spectra, which have a quasicontinuous distribution with superimposed broad structures and sharp peaks, establishes the decay mechanism as due to mixing of a SD state with some of the sea of normal states in which it is embedded. We propose that a conspicuous clustering of γ strength between 1.4 and 2.2 MeV is due to a rearrangement of the level densities by pair correlations. A model was developed to calculate levels from all quasiparticle excitations, as well as the ensuing statistical spectrum from a highly excited state. The calculated statistical spectra reproduce the observed features of the decay spectra, including the differences in even-even and odd-even nuclei. Thus, the decay spectra from SD states are serendipitous probes for the *quenching of pairing with temperature*. The γ spectra associated with the different stages of a γ cascade which flows through SD bands show that the nucleus undergoes an unusual *double cycle of chaos-to-order transition.*

III. Cold States

We found 23 SD bands in the mass 190 region from work done at ATLAS, Gammasphere and Eurogam. (We were the first to establish this region as a new "island" of superdeformation, and have focused much of our effort on superdeformation here.) This large body of data was vital in helping to identify the occurrence of *"identical" bands*, i.e. SD bands in neighboring nuclei which have transition energies with $\Delta E < 1/500$, or which have identical dynamic moments of inertia $\Im^{(2)}$. The identical bands, which were not anticipated, are still not explained, but may imply a symmetry which has yet to be identified. Another striking observation is a staggering of alternate levels in three SD bands in ^{194}Hg, which suggests the presence of a *Y_{44} symmetry* (i.e. four-fold symmetry in a plane perpendicular to the symmetry axis). In addition, we discovered a band in ^{151}Dy, with energies midway between those in ^{152}Dy, which provides additional evidence for *pseudospin symmetry*. In ^{154}Dy we found a SD band which has energies identical to those of an excited SD band in ^{153}Dy and is the first SD band found to decay to prolate collective normal states.

Identification of vibrational states in the SD well can serve to establish the rigidity of the deformation with respect to β, γ or octupole distortions. Theory pointed out that SD nuclei may manifest octupole instability. We found the first indications for an *octupole vibrational band* in ^{190}Hg (from Gammasphere data) at a surprisingly low energy (~600 keV) above the yrast SD band.

We measured lifetimes of individual states of SD bands in ^{192,194}Hg which prove that the deformation is indeed large and that it is stable with respect to spin and particle excitation.

IV. Excited SD States

From Eurogam and Gammasphere data we established that excited SD bands give rise to a pronounced E2 bump in the γ spectrum. This feature allows us to probe the collective properties of excited SD states. There are preliminary indications that the quadrupole moment and moment of inertia of the excited SD states are larger than those of the yrast SD band in ^{192}Hg. We studied the coupling of excited SD and ND states and the mechanism for the unexpectedly large population of SD states by both experiment and theory. We are able to reproduce by Monte Carlo simulations *all observables* connected with the feeding: band intensities, variation of intensity with spin, entry distribution (in spin and energy) of states leading to trapping in the SD well, and the spectra of feeding γ rays.

a.1. Spectrum of γ Rays Connecting Superdeformed and Normal States in ^{192}Hg

(R. G. Henry, T. Lauritsen, T. L. Khoo, M. P. Carpenter, I. Ahmad, B. Crowell, D. Blumenthal, D. Gassmann, R. V. F. Janssens, D. Nisius, 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‡‡)

Almost a hundred superdeformed bands were found in the mass 150 and 190 regions. Nevertheless, the energies and spins of the SD levels are still not measured (with one possible exception). Many attempts were made to decipher the highly-fragmented pathways connecting SD and normal states, but with hitherto no success. We adopted a new approach that consists of characterizing the overall spectral shape of the γ rays linking SD and normal states.

We detected γ rays from the ^{160}Gd(^{36}S,4n)^{192}Hg reaction using Eurogam, a detector array with 43 Compton-suppressed Ge detectors. Pairwise gates were set on known SD transitions in ^{192}Hg in order to obtain the coincident γ–ray spectrum. Gamma rays that precede and follow the SD band can be distinguished on the basis of their Doppler shifts. However, the spectrum of statistical feeding transitions is broad and difficult to extricate by means of the Doppler shift alone; thus it was given by a calculation. We succeeded in isolating the spectrum of γ rays linking SD and "normal" states. The spectrum is comprised (see Figure I-9) of sharp lines and a quasicontinuous component, which has interesting structure. The most striking (and surprising) feature is a broad bump between 1.4 and 2.2 MeV. This spectrum reveals the mechanism for decay out of the SD well: it arises from coupling between a SD state and the sea of normal states in which it is embedded. The spectrum indicates that the decay from the SD state to the normal yrast line takes 3.2 ± 0.6 steps, that the excitation energy of the SD state above yrast is 4.3 ± 0.8 MeV, and spin of the SD state from which the predominant decay takes place has spin 9.5 ± 0.8 ħ.

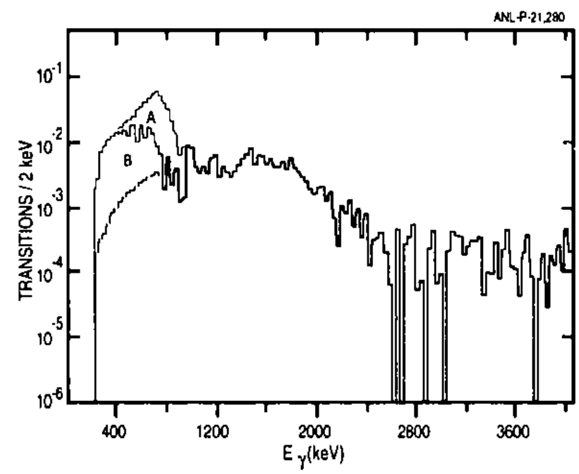

Fig. I-9. Spectrum showing the γ–rays connecting SD and normal states (without the known yrast lines) and transitions (A & B) feeding the SD band.

The different components of the spectrum associated with the formation and decay of SD states reveals an unusual sequence of events, with a transition from chaos to order to chaos to order. A sudden transition from regularly-spaced SD lines to a broad thermal decay spectrum shows that the decay is a result of coupling a cold, ordered, SD system with a hot, chaotic, normal one.

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‡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.

The results were published.[1] The next step is to understand the features of the spectra from decay out of the SD states in terms of the decrease of pair correlations with increasing thermal excitation energy (see B.a.4.). For this purpose, the spectrum from ^{192}Hg is being compared with those from ^{191,194}Hg in order to study the dependence on odd and even particle number, which gives information on the effects of pairing.

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[1]R. G. Henry et al., Phys. Rev. Lett. 73, 777 (1994).

a.2. Spins of Superdeformed Band in ^{192}Hg (T. Lauritsen, T. L. Khoo, R. G. Henry, I. Ahmad, M. P. Carpenter, D. Blumenthal, B. Crowell, D. Gassmann, R. V. F. Janssens, D. Nisius, 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‡‡)

Determination of the spins of SD states is the most important challenge in the study of superdeformation. Knowledge of the spin will provide crucial information on SD bands, in particular on the fascinating phenomenon of bands with identical energies and moments of inertia.

Angular distribution coefficients of the γ rays decaying out of the ^{192}Hg SD band were determined using Eurogam data. These coefficients, as well as the spectral shape and multiplicity of the spectrum, are compared with the results of calculations, thereby providing a check on these calculations. From the measured decay multiplicity and the calculated average spin removed per photon (0.3 $\hbar$), we deduce the average spin $\bar{I}_{decay}$ removed by the γ rays connecting SD and normal states. The spin I_{SD} of the SD band from which the decay occurs is given by $I_{SD} = \bar{I}_{decay} + \bar{I}_{ND}$, where $\bar{I}_{ND}$ is the average spin removed by the normal yrast states. The state from which the major decay out of the SD band occurs is found to have spin $9.5 \pm 0.8\ \hbar$. Since angular momentum is quantized, this leads to a spin assignment of 9 or 10 $\hbar$. The latter value is favored since the yrast band in the SD well must have only even spin values. This constitutes the first deduction of spin from data in the mass 150 and 190 regions. The spin of 10 $\hbar$ agrees with the spin which is inferred from a model, using the observed moment of inertia $\Im^{(2)}(\omega)$.

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a.3. Spectrum of γ Rays from the Decay of SD to Normal States in ^{191}Hg (D. Gassmann, T. L. Khoo, T. Lauritsen, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, B. Crowell, D. Blumenthal, D. Nisius, R. G. Henry, T. Døssing, S. Harfenist, J. R. Hughes,‡ J. A. Becker,‡ M. J. Brinkman,‡ B. Cederwall,§ M. A. Deleplanque,§ R. M. Diamond,§ J. E. Draper,¶ C. Duyar,¶ P. Fallon,§ E. A. Henry,‡ R. W. Hoff,‡ I. Y. Lee,§ E. Rubel,¶ F. S. Stephens,§ and M. A. Stoyer‡)

In B.a.7. we propose that the statistical spectrum emitted from a sharp single excited state serves as a probe of pairing in excited states. A specific test of this proposal is the comparison of the spectra from even-even and odd-even nuclei. Whereas a pair gap exists in an even-even nucleus, it gets filled in an odd-even nucleus. Consequently, low-energy transitions can arise in the latter case, whereas they are calculated to be absent in the former case because very few levels exist in the cold

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gap region. In addition, transitions between 1.4 - 2.2 MeV, which "jump" across the gap, are predicted to have lower yield in the odd-even nuclei. Serendipitously, decay from a superdeformed state serves as a good initial excited sharp state.

We extracted the spectrum pairwise-coincident with SD lines in ^{191}Hg from Gammasphere data and compared it with the equivalent spectra from the even-even nuclei ^{192,194}Hg (see Figure I-10). The differences that are predicted to occur are indeed observed. Thus, the data support our proposal that the reduction of pairing with thermal excitation energy can be probed with statistical decay spectra.

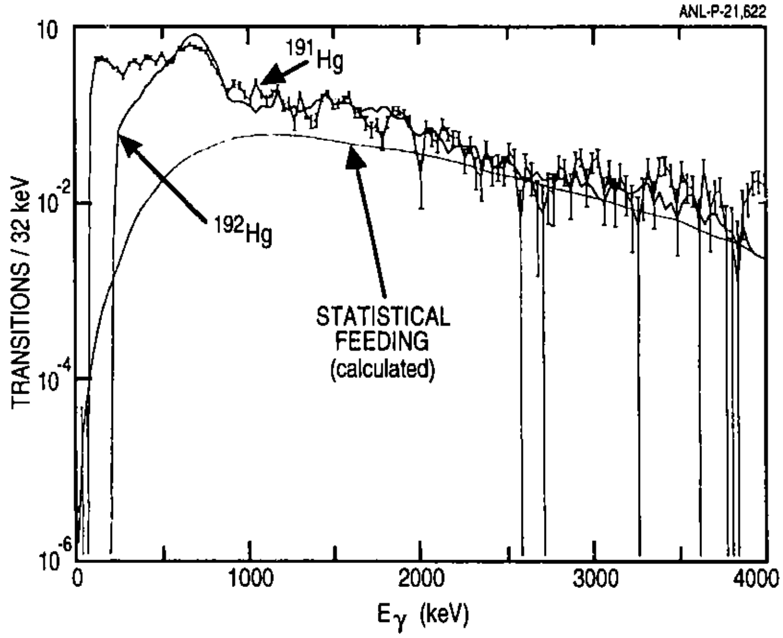

Fig. I-10. Spectra obtained by pairwise gates on the SD lines of ^{191,192}Hg. The smooth line is a calculated spectrum of statistical γ rays feeding the SD band in ^{192}Hg.

a.4. Decay from the Superdeformed Bands in ^{194}Hg (R. G. Henry, T. L. Khoo, M. P. Carpenter, I. Ahmad, B. Crowell, D. Blumenthal, T. Døssing, S. Harfenist, R. V. F. Janssens, D. Gassmann, J. R. Hughes,* J. A. Becker,* M. J. Brinkman,* B. Cederwall,† M. A. Deleplanque,† R. M. Diamond,† J. E. Draper,‡ C. Duyar,‡ P. Fallon,† E. A. Henry,* R. W. Hoff,* I. Y. Lee,† E. Rubel,‡ F. S. Stephens,† and M. A. Stoyer*)

Superdeformed bands in ^{194}Hg were studied using the early implementation of Gammasphere. The response functions for the Ge detectors were measured for the first time as part of this experiment. Experiments were performed with both a backed target (where the residue stopped in the Au backing) and a thin target (where the residue recoiled into vacuum). This will permit measurements of the decay times of the quasicontinuum γ rays. The spectrum in coincidence with the yrast SD band in ^{194}Hg reveals the same features as found in the quasicontinuum structure in ^{192}Hg (see B.a.1.) (see Figure I-11). These features include: statistical γ rays feeding the SD band, a pronounced E2 peak from

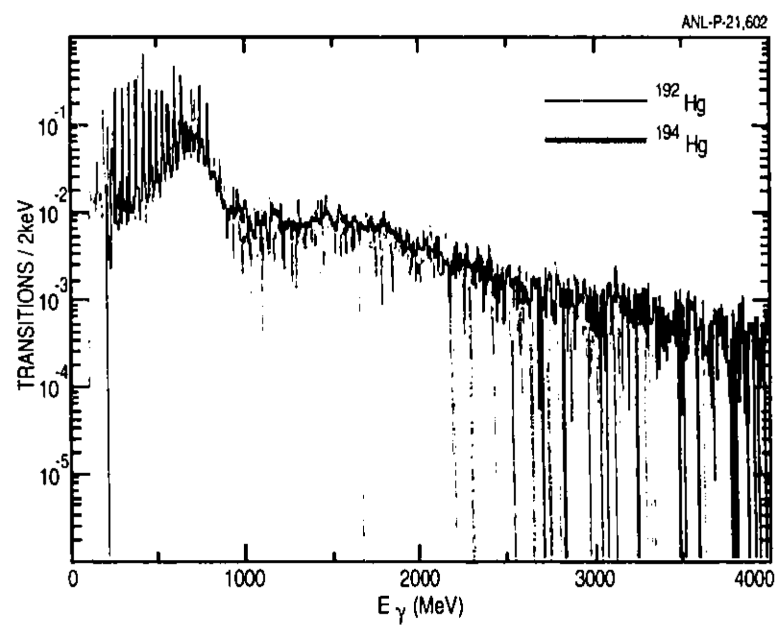

Fig. I-11. Spectra from pairwise gates on SD lines in ^{192,194}Hg.

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transitions feeding the SD band, a M1/E2 bump at low energies that is associated with the last stages of feeding of the superdeformed band, and a quasicontinuous distribution from γ rays linking SD and normal states, including a sizable clustering of strength around 1.7 MeV.

The remarkable similarity of the spectra coincident with SD bands in ^{192,194}Hg provides additional support for a statistical process for decay out of the SD states. This similarity contrasts with differences observed in the spectrum coincident with the SD band in the odd-even ^{191}Hg, confirming the predictions about the role of pairing (in normal states) in influencing the shape of the decay-out spectrum (see B.a.7.).

a.5. The Quasicontinuum of Gamma Rays from the Feeding and Decay of the Superdeformed in ^{194}Pb (T. Lauritsen, I. Ahmad, M. P Carpenter, B. Crowell, R. G. Henry, R. V. F. Janssens, T. L. Khoo, D. Nisius, M. J. Brinkman,† A. E. Henry,† and J. A. Becker†)

Over the last year we developed techniques for the study of the quasicontinuum of gamma-rays from both the feeding and especially the decay of the superdeformed (SD) bands in the Hg nuclei, most notably ^{192}Hg. From this analysis we could extract both the spin and energy of some of the SD bands. The quasicontinuum analysis is the only technique so far that could extract these two fundamental properties of the now more than 100 SD bands found in the A = 150 and A = 190 regions. We based our understanding of the feeding and decay on comparisons of the data with extensive Monte Carlo simulations of the emission of gamma rays, both from the entry distribution toward the SD minimum, and, at lower spins, from the decay out of the SD band back to the states in the normal well.

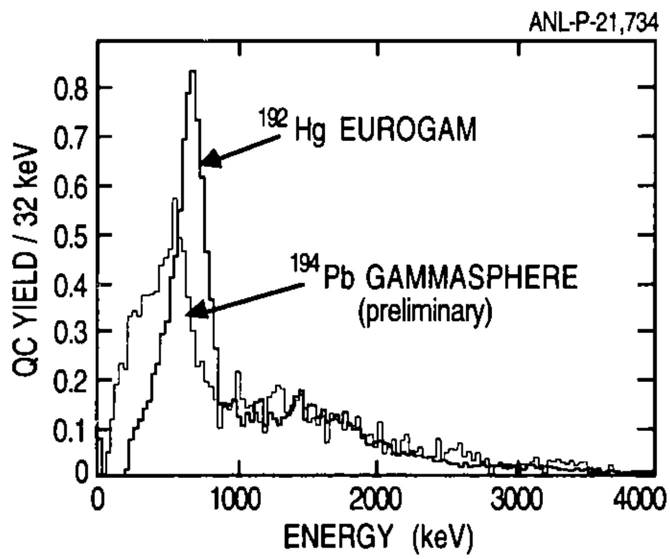

Fig. I-12. Spectrum of γ rays connecting SD and normal states in ^{194}Pb.

It is very important to expand this analysis to other nuclei in order to, among other things, i) confirm the method ii) look for changes of the secondary SD minimum and iii) confirm that the method allows us to study the pairing gap in the nuclei. ^{194}Pb, with its closed proton shell, provides a good testing ground for our understanding of the feeding and decay of its SD bands. We obtained a very large data set for ^{194}Pb from the LLNL group taken with the Gammasphere array. We are analyzing this data set and extracting the quasicontinuum of gamma rays. Preliminary results suggest that the quasicontinuum in ^{194}Pb (see Figure I-12) is similar to that in ^{192}Hg.

To unravel the feeding and decay parts of the quasicontinuum it may be necessary to measure the entry distribution associated with the feeding of the SD band in this nucleus. We are evaluating whether we can do this at the Argonne Notre Dame array at ATLAS or whether we need to use the GASP detector array at Legnaro, Italy. Fission and the weak population the SD band may require us to use the more powerful array in Italy, which just like the Argonne array has the necessary inner ball of BGO detectors.

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a.6. Search for Two-γ Sum-Energy Peaks in the Decay Out of Superdeformed Bands (D. Blumenthal, T. L. Khoo, T. Lauritsen, T. Døssing, I. Ahmad, M. P. Carpenter, B. Crowell, D. Gassmann, R. G. Henry, R. V. F. Janssens, and D. Nisius)

The spectrum of γ rays decaying out of the superdeformed (SD) band in ^{192}Hg has a quasicontinuous distribution. Whereas methods to construct level schemes from discrete lines in coincidence spectra are well established, new techniques must still be developed to extract information from coincidences involving quasicontinuous γ rays. From an experiment using Eurogam, we obtained impressively clean 1- and 2-dimensional γ spectra from pairwise or single gates, respectively, on the transitions of the SD band in ^{192}Hg. We investigated methods to exploit the 2-dimensional quasicontinuum spectra coincident with the SD band to determine the excitation energy of the SD band above the normal yrast line. No strong peaks were observed in the 2-γ sum spectra; only candidates of peaks at a 2-3 σ level were found. This suggests that 2-γ decay is not the dominant decay branch out of SD bands, consistent with the observed multiplicity of 3.2 (see B.a.1.). We shall next search for peaks in sum-spectra of 3 γs.

a.7. Calculation of the Spectrum of γ Rays Connecting Superdeformed and Normally Deformed Nuclear States (T. Døssing, T. L. Khoo, T. Lauritsen, I. Ahmad, D. Blumenthal, M. P. Carpenter, B. Crowell, D. Gassmann, R. G. Henry, R. V. F. Janssens, and D. Nisius)

The decay out of superdeformed states occurs by coupling to compound nuclear states of normal deformation. The coupling is very weak, resulting in mixing of the SD state with one or two normal compound states. With a high energy available for decay, a statistical spectrum ensues. The shape of this statistical spectrum contains information on the level densities of the excited states below the SD level. The level densities are sensitively affected by the pair correlations. Thus decay-out of a SD state (which presents us with a means to start a statistical cascade from a highly-excited sharp state) provides a method for investigating the reduction of pairing with increasing thermal excitation energy.

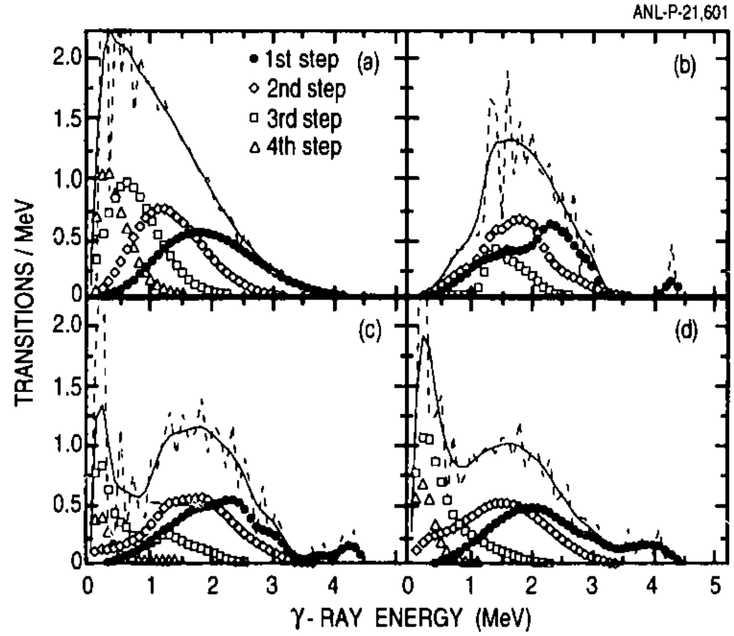

Fig. I-13. Statistical decay spectra, with 100-keV bins, for initial energy U = 4.3 MeV (dashed lines) calculated with (a) the unpaired even-even level density, and (b-d) with the level densities obtained in the diagonalization procedure with (b) even-even, (c) odd-even and (d) odd-odd particle numbers. The solid lines in the panels are obtained by folding the spectra by a Gaussian function of FHWM = 0.3 MeV, chosen to be equal to the distance between doubly-degenerate neutron single-particle levels. The contributions to the full spectrum from individual cascade steps, denoted by the symbols in panel (a), are also folded by the Gaussian function.

The energies of 0, 2, 4... quasiparticle states are calculated using a BCS approximation with a self-consistent pair field, followed by particle-number projection and diagonalization. A step-wise reduction of the pair correlation energy with increasing quasiparticle number is obtained. The resultant levels are used to calculate the statistical spectrum from an initial state 4.3 MeV above the yrast line. Spectra for even-even, odd-even and odd-odd nuclei were calculated (see Figure I-13), and characteristic features for each type are observed. Qualitative agreement with the decay-out spectra from SD bands in ^{192}Hg (even-^{130}Te(^{64}Ni,3n)^{191}Hg reactions. To ensure that any observed effect was not due to a simple even) and ^{191}Hg (odd-even) are observed, indicating that structures in the spectra are due to pairing effects.

Future work will use realistic single-particle energies from the cranked shell-model (instead of the schematic equispaced single-particle levels used so far), and on allowing for removal of angular momentum in the statistical decay. The calculated decay-out multiplicity is ~ 25% lower than the experimental one; the cause for this will be searched. The calculations will also be extended for comparison with spectra following neutron capture.

a.8. Spectra of γ Rays Feeding Superdeformed Bands (T. Lauritsen, T. L. Khoo, T. Døssing, R. G. Henry, I. Ahmad, D. Blumenthal, M. P. Carpenter, B. Crowell, R. V. F. Janssens, and D. Nisius)

The spectrum of γ rays coincident with SD transitions contains the transitions which populate the SD band. This spectrum can provide information on the feeding mechanism and on the properties (moment of inertia, collectivity) of excited SD states. We used a model we developed to explain the feeding of SD bands, to calculate the spectrum of feeding γ rays. The Monte Carlo simulations take into account the trigger conditions present in our Eurogam experiment (see B.a.1.). Both experimental and theoretical spectra contain a statistical component and a broad E2 peak (from transitions occurring between excited states in the SD well) (see Figure I-9).

There is good resemblance between the measured and calculated spectra although the calculated multiplicity of an E2 bump is low by ~ 30%. Work is continuing to improve the quality of the fits, which will result in a better understanding of excited SD states. In addition, a model for the last steps, which cool the γ cascade into the SD yrast line, needs to be developed. A strong M1/E2 low-energy component, which we believe is responsible for this cooling, was observed.

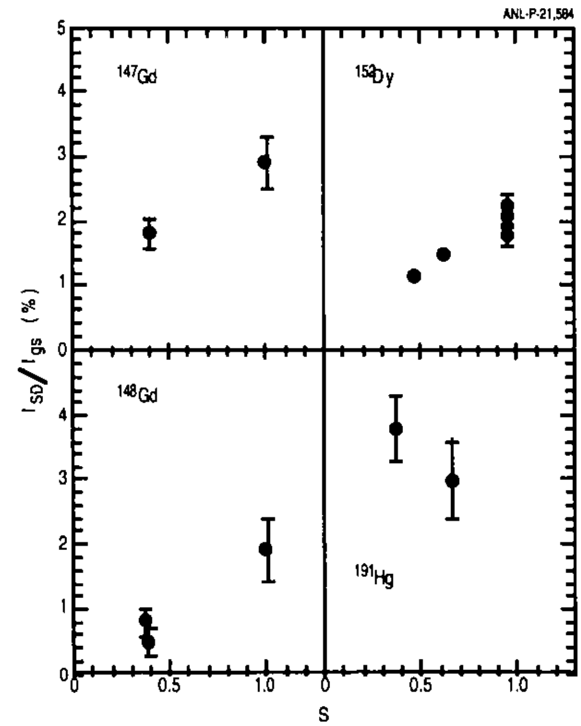

Fig. I-14. Synopsis of SD band population intensities as a function of the mass-symmetry S at the entrance channel. The parameter S is defined as $S = 1-(|A_t - A_b|)/(A_t + A_b)$. The data on $^{147,148}Gd$ and ^{152}Dy are from published literature.

a.9. Search for Entrance-Channel Dependence in the Population of Superdeformed Bands in ^{191}Hg (F. Soramel,* T. L. Khoo, R. V. F. Janssens, I. Ahmad, M. P. Carpenter, T. Lauritsen, Y. Liang,† E. F. Moore,‡ Ph. Benet,§ K. B. Beard,|| I. Bearden,§ P. J. Daly,§ M. W. Drigert,¶ B. Fornal,§ U. Garg,|| Z. Grabowski,§ R. Mayer,§ W. Reviol,|| and D. Ye||)

The population intensity of some SD bands in the mass 150 region were observed to depend on the mass symmetry of the entrance channel in the fusion reaction. The authors raised the possibility that the population of SD bands had a memory of the entrance channel. To check this interesting possibility, we made measurements of the population intensities of superdeformed (SD) bands in the $^{160}Gd(^{36}S,5n)^{191}Hg$ and

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$^{130}Te(^{64}Ni,3n)^{191}Hg$ reactions. To ensure that any observed effect was not due to a simple angular momentum difference in the entrance channels, we also measured the average entry points and spin distributions of normal and SD states in ^{191}Hg in the two reactions (see Figure I-14). The entry points and spin distributions for ^{191}Hg are the same and, indeed, so are the SD intensities in the two reactions. Hence, no entrance-channel effect is observed in the population of the SD band in ^{191}Hg, in contrast with data for SD bands in the mass 150 regions. We suggest that the effect observed previously in the mass 150 region is due to an angular momentum effect. A letter reporting our results was submitted for publication.

a.10. Search for Excited Superdeformed Bands in ^{151}Dy (D. Nisius, R. V. F. Janssens, B. Crowell, I. Ahmad, M. P. Carpenter, R. G. Henry, T. L. Khoo, T. Lauritsen, P. Fallon,† B. Cederwall,† M. A. Deleplanque,† R. M. Diamond,† I. Y. Lee,† A. O. Machiavelli,† F. S. Stephens,† P. J. Daly,‡ Z. W. Grabowski,‡ R. M. Mayer,‡ and P. J. Twin§)

Following the first report[1] of superdeformed (SD) bands with identical transition energies in the pairs ($^{151}Tb^*$,^{152}Dy), ($^{150}Gd^*$,^{151}Tb) and ($^{153}Dy^*$,^{152}Dy) (where * denotes an excited SD band), it was proposed by Nazarewicz et al.[2] that the observations could be understood in a strong-coupling approach if pseudo SU(3) symmetry were invoked. In this model there are three limiting values of the decoupling parameter; i.e. a = 0, ±1. In the first two cases mentioned above the pairs of bands have nearly identical transition energies and are interpreted as proton excitations involving the [$\tilde{2}\tilde{0}\tilde{0}$]1/2 pseudospin orbital coupled to the ^{152}Dy core, for which the value of the decoupling parameter is calculated to be a = +1.

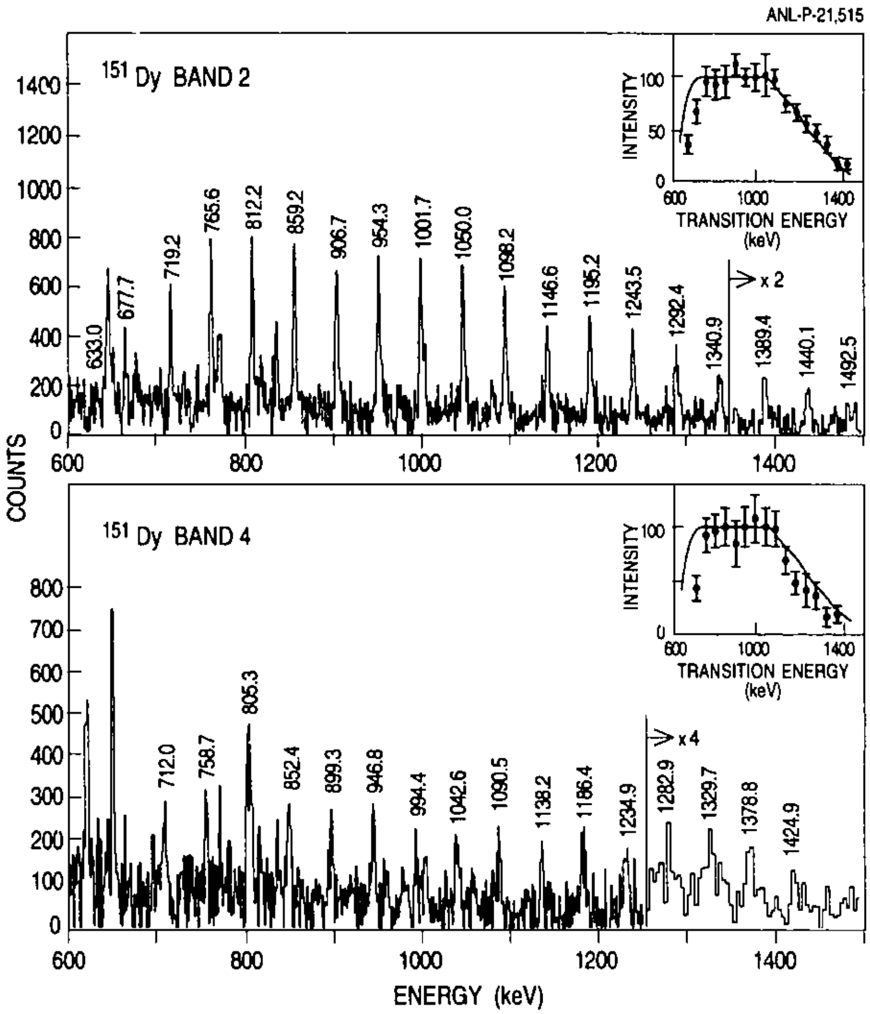

Fig. I-15. Spectra obtained for band 2 (top) and band 4 (bottom) in ^{151}Dy. The insets compare the intensity patterns of bands 2 and 4 (data points) with that of the ^{152}Dy SD band (curve). Note that the highest energy parts of the top and bottom spectra were compressed by a factor of 2 and 4, respectively.

†Lawrence Berkeley Laboratory, ‡Purdue University, §Liverpool University, UK

[1]T. Byrski et al., Phys. Rev. Lett. 64, 1650 (1990), [2]W. Nazarewicz et al., Phys. Rev. Lett. 64, 1654 (1990), [3]G.-E. Rathke et al., Phys. Lett B209, 177 (1988).

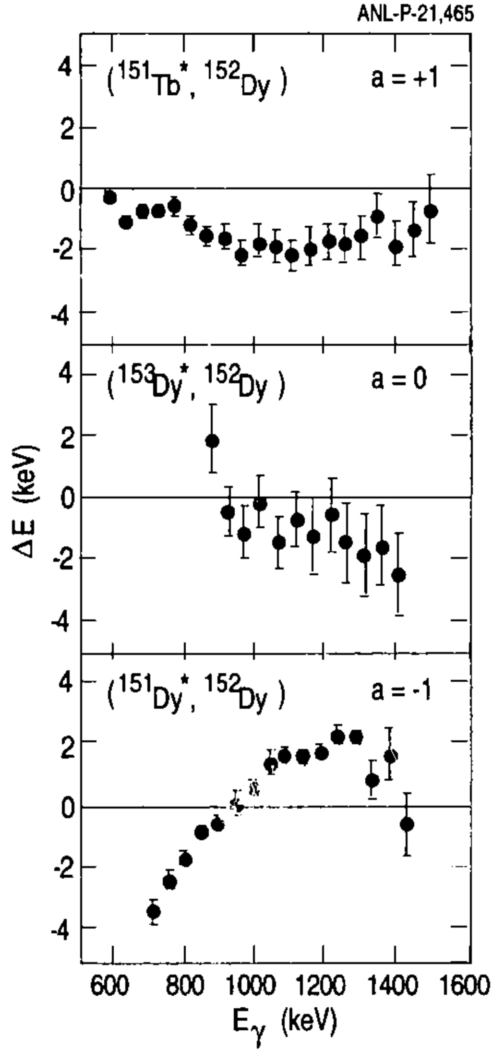

Fig. I-16. Comparison between the pairs of identical SD bands corresponding to the three limiting values a = +1,0,-1 of the decoupling parameter. For the (^{151}Tb,^{152}Dy) pair (top), the points in the figure represent the differences between transition energies in the two SD bands. For the (^{153}Dy*,^{152}Dy) pair (middle), the differences are calculated from the average energies of consecutive transitions in the two signature partner bands of ^{153}Dy and the γ-ray energies in ^{152}Dy. In the (^{151}Dy*,^{152}Dy) comparison (bottom), the differences were obtained by subtracting the average energies of consecutive transitions in ^{152}Dy from the γ-ray energies of band 4 in ^{151}Dy.*

The (^{153}Dy*,^{152}Dy) pair involves a [514]9/2 neutron coupled to the ^{152}Dy core resulting in a decoupling parameter a = 0. In this pseudospin framework Nazarewicz predicted that there should be an excited SD band in ^{151}Dy based on a decoupling parameter of a = -1. This band should have transition energies lying at the midway points of those in the core ^{152}Dy band.

Using the early implementation phase of Gammasphere, SD bands were studied in ^{151}Dy with the ^{122}Sn(^{34}S,5n) reaction at a beam energy of 175 MeV. These are the reaction conditions under which the yrast SD band of ^{151}Dy was first discovered at ATLAS.[3] A total of 1.3 × 10^9 triple and higher fold coincidence events were recorded in the four-day run.

Five SD bands were observed in ^{151}Dy. In addition to the yrast SD band, four new bands with dynamic moments of inertia $\Im^{(2)}$ similar in magnitude to that seen in band 1 were found. These four SD bands have respective intensities of 39(7), 30(5), 20(7) and 13(4)% relative to the intensity of band 1. The yrast SD band carries about 1% of the total gamma-ray flux reaching the ^{151}Dy ground state. Also seen in the data were the yrast SD bands in the 4n and p4n reactions channels, ^{152}Dy and ^{151}Tb.

Band 4, the band with 20% the intensity of band 1, has transition energies which lie midway to those of the ^{152}Dy yrast SD band and, therefore, the $\Im^{(2)}$ moments of inertia are nearly identical (see Fig. I-15 and I-16). This band can be associated with a neutron hole excitation involving the $[\tilde{3}\tilde{1}\tilde{0}]1/2$ pseudospin orbital and is then the band based on the a = -1 decoupling parameter as suggested by Nazarewicz et al. Band 2 has transition energies that lie at the 3/4 points to the ^{152}Dy band above 1 MeV (see Fig. I-15). In the strong coupling approach this band has tentatively been assigned as a [642]5/2 neutron hole coupled to the ^{152}Dy core. Configuration assignments for the other bands are less straightforward and were not yet proposed. A paper reporting the results was accepted for publication.

An experiment will be performed soon to determine in the same measurement the deformations associated with band 4 in ^{151}Dy and with the ^{152}Dy yrast band. The major advantage of this measurement is that since both bands were produced under the same experimental conditions, the major source of error associated with lifetime measurements (i.e. the uncertainty of the stopping power) is eliminated. Thus, a differential lifetime measurement between the two bands can be made and small differences in deformation can be determined.

a.11. Superdeformation Studies in ^{150}Tb and ^{153}Ho (D. Nisius, R. V. F. Janssens, B. Crowell, I. Ahmad, M. P. Carpenter, R. G. Henry, T. L. Khoo, T. Lauritsen, S. Asztalos,† P. Fallon,† B. Cederwall,† M. A. Deleplanque,† R. M. Diamond,† I. Y. Lee,† A. O. Machiavelli,† F. S. Stephens,† P. J. Twin,‡ C. W. Beausang,‡ M. Bergstrom,‡ and S. Clarke‡)

There are now over 40 superdeformed (SD) bands known in the A ~ 150 region and in most cases the properties of these bands are understood in terms of single-particle excitations in the absence of pairing. By continuing the search for new SD bands we hope to gain insight into (i) the ordering of the proton and neutron orbitals near the Fermi surface in the SD well, (ii) the effects that the alignment of those orbitals has on the moments of inertia and (iii) the collective excitations in the SD well. For ^{150}Tb, which is one proton and one neutron away from the SD doubly-magic nucleus ^{152}Dy, it should be possible to study SD bands based on both proton and neutron hole excitations. By adding one proton to the ^{152}Dy nucleus (i.e. ^{153}Ho) proton excitations above the Z = 66 shell gap can be studied. These excitations are important as calculations suggested that the proton intruder orbital N = 7 might become occupied. Interactions between this orbital and a N = 5 level may result in softness towards octupole vibrations.

High spin states in ^{150}Tb and ^{153}Ho were populated using the ^{124}Sn(^{31}P,5n) and ^{120}Sn(^{37}Cl,4n) reactions, respectively. In both cases the early implementation phase of Gammasphere was used to detect the decay gamma rays and over 1×10^9 triple and higher fold coincidence events were recorded. In ^{150}Tb, the data analysis is complete and two new SD bands were identified. The fact that $\Im^{(2)}$ moments of inertia are sensitive to the specific high-N intruder content of the SD bands was used to suggest configurations for the two new bands. A paper reporting these results is being prepared. For ^{153}Ho, data analysis is still in its early stages.

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†Lawrence Berkeley Laboratory, ‡Liverpool University, United Kingdom.

a.12. Search for Superdeformed Bands in ^{154}Dy (D. Nisius, R. V. F. Janssens, T. L. Khoo, I. Ahmad, D. Blumenthal, M. P. Carpenter, B. Crowell, D. Gassmann, T. Lauritsen, W. C. Ma,‡ J. H. Hamilton§, A. V. Ramayya,§ P. Bhattacharyya,¶ C. T. Zhang,¶ P. J. Daly,¶ Z. W. Grabowski,¶ and R. H. Mayer¶)

The island of superdeformation in the vicinity of the doubly magic ^{152}Dy yrast superdeformed (SD) band is thought to be well understood in the framework of cranked mean field calculations. In particular, the calculations suggested that in ^{154}Dy there should be no yrast or near yrast SD minimum in the 40-60 $\hbar$ spin range, where SD bands in this mass region are thought to be populated. However, with the presence of five SD bands in the neighboring ^{153}Dy nucleus,[1] it is necessary to ascertain if the addition of one single neutron diminishes the importance of shell effects to the extent that superdeformation can no longer be sustained.

In an experiment utilizing the increased resolving power of the early implementation phase of Gammasphere, the reaction ^{122}Sn(^{36}S,4n) at 165 MeV was employed to populate high spin states in ^{154}Dy. In a four-day run with 36 detectors, over one billion triple and higher fold coincidence events were recorded. One new SD band was identified and was assigned to ^{154}Dy. This band is shown in Fig. I-17. From comparisons with the $\Im^{(2)}$ moments of inertia of the SD bands in ^{152}Dy

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‡Mississippi State University, §Vanderbilt University, ¶Purdue University,
[1]B. Cederwall et al., to be published.

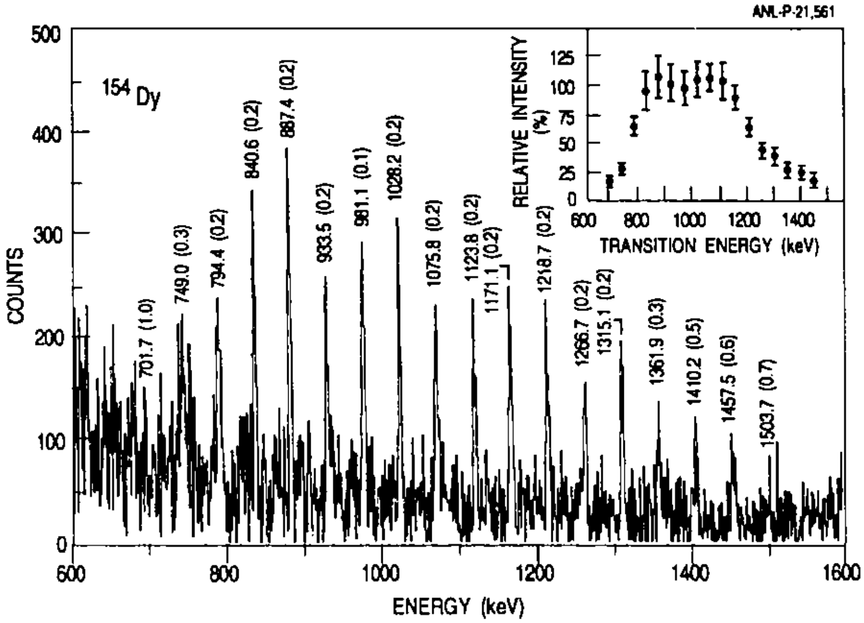

Fig. I-17. The SD band of ^{154}Dy obtained from a sum of double coincidence gates. The energies of the transitions are given in keV, together with the errors (presented in parentheses). The inset shows the intensity profile in the SD band.

and ^{153}Dy, a configuration based on ([514]9/2)^2 neutrons coupled to the ^{152}Dy SD core was proposed. One unexpected and as yet unexplained feature of this new SD band is that the transition energies are almost identical to those of an excited SD band in ^{153}Dy. It is also worth noting that the feeding of the yrast states is similar to that achieved by the deexcitation from the ensemble of all entry states in the reaction. This observation emphasizes the statistical nature of the decay-out process. A paper reporting these results was accepted for publication.

a.13. Search for Extremely Deformed Systems in ^{182}Os (M. P. Carpenter, R. R. Chasman, R. V. F. Janssens, I. Ahmad, B. Crowell, R. Henry, T. L. Khoo, T. Lauritsen, D. Nisius)

We performed an experiment at Gammasphere to search for elongated shapes in the nucleus ^{182}Os. Recent calculations by R. R. Chasman[1] show that this nucleus is the most promising for finding structures with major to minor axis ratios of 2.2:1 or greater. These calculations include a necking degree of freedom which is thought to be an improvement over past cranked Strutinsky calculations where predictions for extended shapes in Yb and Er nuclei were made.

In order to populate ^{182}Os at spins > 60 $\hbar$, we utilized the ^{138}Ba(^{48}Ca,4n) reaction. The target was made by evaporating ^{138}Ba onto a 500-µg/cm^2 Au foil, followed by the evaporation of ~250-µg/cm^2 Au onto the exposed side of the Ba. Such a target was necessary since Ba is highly reactive with oxygen. Even after taking this precaution, the target suffered oxidation which adversely effected the quality of our data. The experiment was performed at Gammasphere using the predetermined energy of 220 MeV. A single target was used and the ^{138}Ba had a thickness of 750 µg/cm^2. The run lasted four days and ~ 440 × 10^6 3-fold and higher Compton-suppressed Ge events were collected.

No strong evidence for highly deformed structures was found in this data set. However, it is our belief that the oxygen contamination in our target greatly compromised the outcome of the experiment. Much of the background in our total projection is due to fusion reactions of ^{48}Ca on oxygen isotopes. The resulting γ rays are highly Doppler broadened and experience larger Doppler shifts relative to the Os residues. Thus, these γ rays are spread out over the entire energy spectrum almost uniformly adding to the background. Our conclusion is that due to target problems, only 150-200 million of the coincidence events can be associated with Os-like residues. Therefore, we do not believe that the negative result from this experiment negates the prediction that the 2.2:1 minimum can be probed in spectroscopic studies.

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[1]R. R. Chasman, Phys. Lett. B302, 134 (1993).

a.14. Inter-Band Coincidences in the Superdeformed Well of ^{190}Hg from Gammasphere (B. Crowell, M. P. Carpenter, R. V. F. Janssens, R. G. Henry, I. Ahmad, T. L. Khoo, T. Lauritsen, and D. T. Nisius)

Very few experimental observables are ordinarily accessible for superdeformed (SD) states in the A ~ 150 and A ~ 190 regions. The gamma-decay out of the superdeformed bands usually proceeds directly to the normally deformed states, through highly fragmented pathways, making it difficult to determine the spins, parities and excitation energies of the SD states. The in-band E2 transitions are so collective (2×10^3 single-particle units in the A ~ 190 region) that it is typically impossible to detect any of the competing M1 and E1 transitions between states in the SD well.

In two recent experiments at Gammasphere, we detected an excited SD band in the nucleus ^{190}Hg which decays to the previously observed vacuum SD band in that nucleus, rather than decaying into the sea of highly excited normally deformed states, as is the case for all other known SD bands in the A ~ 150 and A ~ 190 regions. Gamma-ray coincidence relationships are observed between the two bands which show that the depopulation of the excited band occurs gradually, over the range of rotational frequencies between 0.25 and 0.30 MeV. The moment of inertia of the excited band displays a behavior which is unique for an even-even nucleus in the A ~ 190 region of superdeformation, maintaining a constant value of $\Im^{(2)} = 125$ MeV^{-1} throughout the entire observed range of angular frequencies, from 0.25 to 0.35 MeV (see Fig. I-18). All other even-even nuclei in the region show $\Im^{(2)} \approx 90\text{-}100$ MeV^{-1} at low spins, with a marked increase continuing up to the highest spins observed. Even more intriguing is the recent prediction, using generator coordinate calculations, of the characteristics of the one-phonon octupole-vibrational states in the superdeformed well.[1] Extremely strong E1 transitions are predicted to exist between the one-phonon and zero-phonon bands, and quadrupole-octupole coupling effects are predicted to be important, possibly accounting for the unprecedentedly large moment of inertia of the excited band we observed.

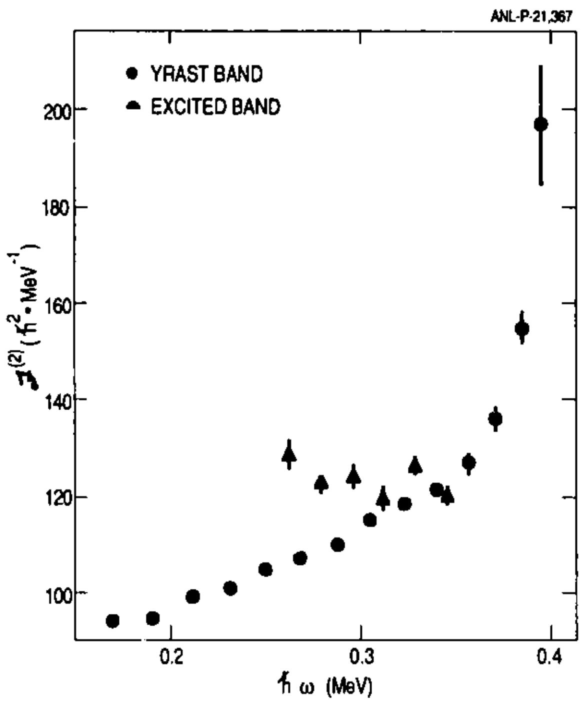

Fig. I-18. The dynamic moment of inertia $\Im^{(2)}$ as a function of rotational frequency $\hbar\omega$ for the two SD bands in ^{190}Hg.

We also extended the vacuum SD band to higher and lower rotational frequencies, and detected a sharp increase in the moment of inertia at $\hbar\omega = 0.38$ MeV. This apparent observation of a band-crossing is in good agreement with the most recent Hartree-Fock calculations.

In order to locate the actual discrete transitions that connect the two bands, a second experiment was performed (see below). The identification of these transitions, and the measurement of their angular distributions would allow, for the first time, the experimental determination of the relative spins and excitation energies of two superdeformed bands.

[1]P. Bonche et al., to be published.

a.15. Evidence for Octupole Vibration in the Superdeformed Well of ^{190}Hg from Eurogam

(B. Crowell, M. P. Carpenter, R. V. F. Janssens, D. J. Blumenthal, I. Ahmad, T. Lauritsen, T. L. Khoo, D. Nisius, J. Timar,† A. N. Wilson,† J. F. Sharpey-Schafer,† T. Nakatsukasa,‡ A. Astier,§ F. Azaiez,¶ L. du Croux,§ B. J. P. Gall,|| F. Hannachi,** A. Korichi,¶ A. Lopez-Martens,** M. Meyer,§ E. S. Paul,† M. G. Porquet,** and N. Redon§)

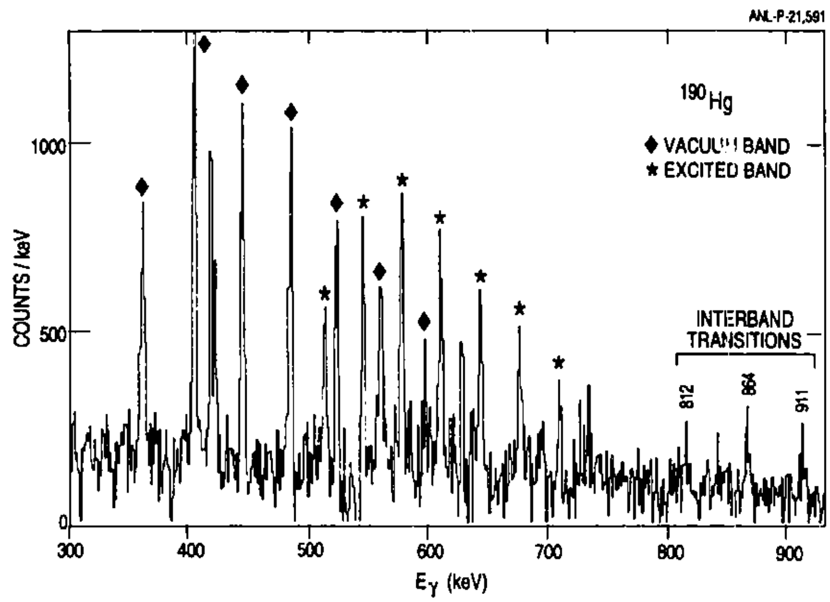

Fig. I-19. Sum of combinations of double coincidence gates yielding events in which the excited SD band was populated. The pairs of coincidence gates consisted of combinations of transitions in the excited SD band with other transitions in the excited band, plus transitions in the excited band with transitions in the lowest SD band. The interband dipole transitions are clearly indicated.

Gammasphere experiments in 1993-94 brought to light the existence of an excited superdeformed (SD) band in ^{190}Hg[1] with the unusual property of decaying entirely to the lowest (yrast) SD band over 3-4 transitions, rather than to the normally deformed states as is usually the case in the A ~ 150 and A ~ 190 regions of superdeformation. Although M1 transitions between signature-partner SD bands were previously observed in ^{193}Hg,[2] no such mechanism was available to explain the situation in the even-even nucleus ^{190}Hg, whose yrast SD band has no signature partner. The best explanation appears to lie in long-standing theoretical predictions that the SD minimum in the potential energy surface would be quite soft with respect to octupole vibrations. This would lead to enhanced E1 transitions connecting the one-phonon and zero-phonon states. The data and this interpretation were published. A shortcoming of the Gammasphere experiments was that they did not allow the definitive measurement of the energies of the gamma-ray transitions connecting the two bands, due to the very weak population of the excited band (~0.05% of the ^{190}Hg channel) and also partly, we believed, to the angular distributions of the transitions, which were peaked near 90 degrees, where Gammasphere had few detectors.

An experiment was therefore performed using the Eurogam Phase II spectrometer, which was more efficient than the partially completed Gammasphere array, and which has detectors at side angles. This experiment confirmed the existence of the excited SD band. Furthermore, the energies of the interband transitions were firmly established, and Directional Correlation ratios (DCO) were extracted, indicating that the lines are of dipole character (see Fig. I-19). This constitutes a measurement of the relative spins and excitation energies of the two SD bands. RPA calculations performed by Takashi Nakatsukasa are in excellent agreement with the data,

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†University of Liverpool, United Kingdom, ‡Chalk River Laboratories, Ontario, Canada, §Institut de Physique Nucléaire, Lyon, France, ¶IPN, Orsay, France, ||Centre de Recherches Nucleaires, Strasbourg, France, **CSNSM, Orsay, France.

[1]B. Crowell et al., Phys. Lett. B 333, 320 (1994).

[2]M. J. Joyce et al., Ph s. Rev. Lett. 71, 2176 (1993).

supporting the octupole-vibrational interpretation. A paper describing the Eurogam results and the RPA calculations was accepted for publication. We hope this work will lead to experimental tests of some of the other theoretical predictions regarding the octupole degree of freedom at extreme deformations, including the observation of other members of the octupole-vibrational multiplet and the observation of such states in other nuclei in the A ~ 190 region.

a.16. Superdeformation Studies in ^{191}Hg (M. P. Carpenter, R. V. F. Janssens, B. Crowell, I. Ahmad, D. Gassmann, R. G. Henry, T. L. Khoo, T. Lauritsen, D. Nisius, B. Cederwall,† J. A. Becker,‡ M. J. Brinkman,‡ M. A. Deleplanque,† R. M. Diamond,† P. Fallon,† L. P. Farris,‡ U. Garg,§ E. A. Henry,‡ J. R. Hughes,‡ I. Y. Lee,† A. O. Machiavelli,† E. F. Moore,¶ and F. S. Stephens†)

Superdeformation in the A ~ 190 region was first observed in ^{191}Hg from an experiment performed at ATLAS using the Argonne Notre Dame γ-ray facility.[1] We recently revisited the study of superdeformation in this nucleus using Gammasphere and the ^{160}Gd(^{36}S,5n) and ^{174}Yb(^{22}Ne,5n) reactions at 172 and 120 MeV in order to populate and measure states in the second well. The goal of the experiment was to identify new bands in the data, and thus allow us to gain understanding on the relative placement of single particle orbitals near the N = 112 SD shell gap. From an analysis of the data, the three previously identified SD bands were extended, and their feeding into the yrast states delineated. Two new SD bands were observed and preliminary evidence for a third new band was obtained as well.

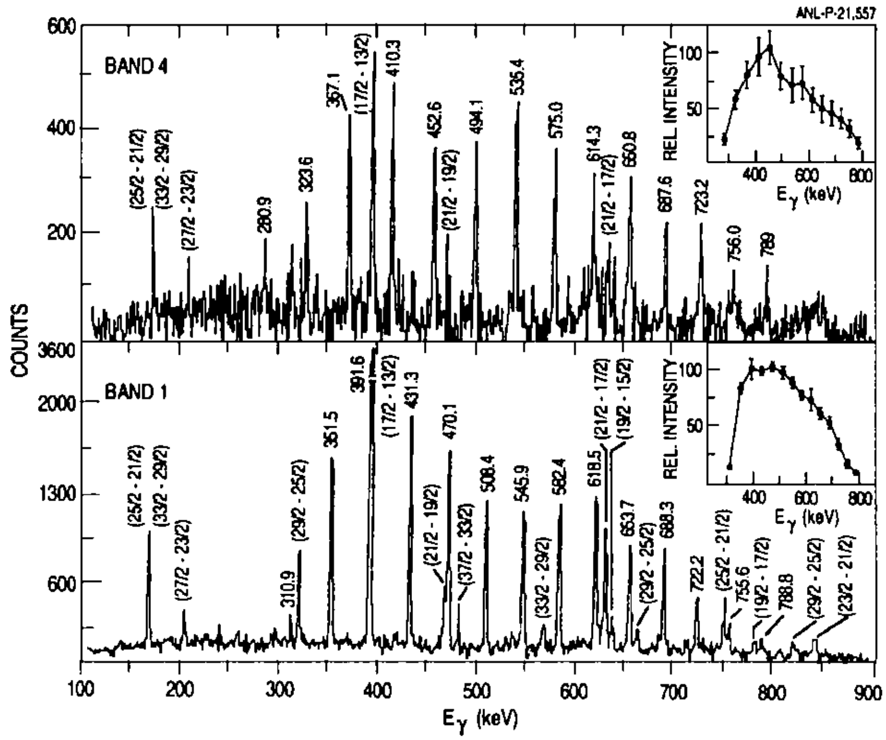

Fig. I-20. Double-gated spectrum for bands 1 and 4 from the new Gammasphere experiment. Each member of the superdeformed bands is labeled by its energy. Other transitions identified in ^{191}Hg are labeled by the spins of the initial and final levels. In the inset for each spectrum is the relative intensity profile for each band.

The strongest of the new SD bands (see Fig. I-20) has properties similar to those of a superdeformed band reported recently in ^{193}Hg.[2] Both bands are believed to be built on the unfavored signature of the $j_{15/2}$ intruder configuration. The analysis of these bands in both nuclei

†Lawrence Berkeley Laboratory, ‡Lawrence Livermore National Laboratory, §University of Notre Dame, ¶North Carolina State University and Triangle Universities Nuclear Laboratory.

[1]E. F. Moore et al., Phys Rev. Lett. 63, 360 (1989). [2]M. Joyce et al., Phys. Lett. B340, 150 (1994).

gave insight into the behavior of the $j_{15/2}$ neutron pair nearest the Fermi surface at the N = 112 gap. The behavior of the SD bands built on two signatures of the $j_{15/2}$ orbital at N = 111 and N = 113 agree well with predictions from cranked shell-model calculations. The other two new SD bands are intriguing in that their transition energies are identical to those of SD bands observed in neighboring nuclei. A paper reporting part of these results was accepted for publication.

a.17. Quasiparticle Excitations in Superdeformed ^{192}Hg (T. Lauritsen, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, B. Crowell, R. G. Henry, T. L. Khoo, P. Fallon,* B. Cederwall,* R. M. Clark,* M. A. Deleplanque,* R. M. Diamond,* B. Gall,† F. Hannachi,† A. Korichi,‡ I. Y. Lee,* A. O. Machiavelli,* C. Schuck,† and F. S. Stephens*)

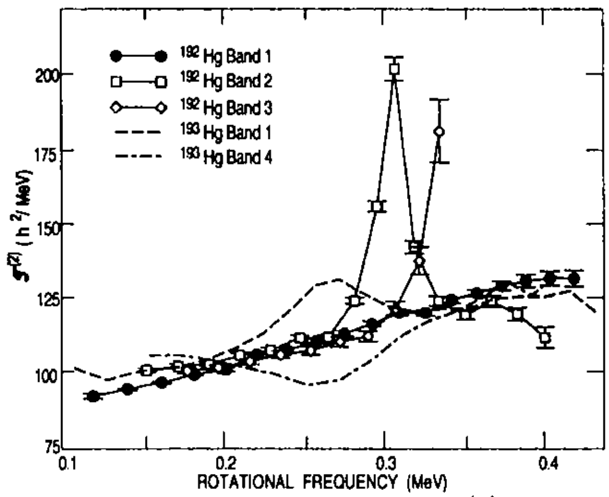

Fig. I-21. Dynamic moments of inertia ($\mathfrak{I}^{(2)} = \frac{4}{\Delta E\gamma}$), where $\Delta E\gamma$ is the in-band transition energies as a function of rotational frequency for the three SD bands assigned to ^{192}Hg. The dashed and dot-dashed lines correspond to ^{193}Hg bands 1 and 4, respectively.

The nucleus ^{192}Hg plays a pivotal role for superdeformation in the mass 190 region, since calculations of single-particle levels show large shell-gaps for the superdeformed (SD) shape at N = 112 and Z = 80. As a result, ^{192}Hg is referred to as the doubly magic SD nucleus for the A = 190 region. In previous studies, only one superdeformed band was observed in this nucleus, and this fact was cited as indirect evidence that large shell gaps do indeed exist at the proposed particle numbers.[1]

Recently, ^{192}Hg was re-examined at Gammasphere using the ^{160}Gd(^{36}S,4n)^{192}Hg reaction at a beam energy of 159 MeV. Two new SD bands in ^{192}Hg were identified and are populated at 10% and 5% relative to band 1. One of the SD bands exhibits a pronounced peak in the dynamic moment of inertia which is interpreted as a crossing between two excited SD configurations involving the N = 7 intruder and [512]5/2 orbitals (see Fig I-21). The second SD band has near-identical transition energies to an excited SD band in ^{191}Hg. A paper reporting these results was submitted.

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*Lawrence Berkeley Laboratory, †Centre de Spectrometrie Nucleaire et de Spectrometrie de Masse, Orsay, France, ‡Institut de Physique Nucleaire,Orsay, France.

[1]D. Ye et al., Phys. Rev. C 41 R9 (1990).

a.18. Lifetimes of an Excited Superdeformed Band in ^{192}Hg (I. Ahmad, D. Blumenthal, M. P. Carpenter, B. Crowell, T. Døssing, R. G. Henry, R.V.F. Janssens, T. L. Khoo, G.Smith,* T. Lauritsen, F. Hannachi,* I. Deloncle,* B. Gall,* M. G. Porquet,* C.Schuck,* 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††)

An excited superdeformed band was identified in ^{192}Hg (see a.17.) and the lifetimes of its levels measured with the Doppler-shift attenuation method from data taken with the Eurogam spectrometer. The band is proposed to be based on the two-quasineutron {ν[642]3/2 [512]5/2} configuration, which after a band crossing, becomes the {ν[642]3/2 [752]5/2} configuration. The transition quadrupole moment Q_t of the excited band is the same as that of the yrast SD band, within experimental errors. This suggests that the deformation of the SD minimum is robust with respect to quasiparticle excitation, despite the occupation of the deformation-driving ν[752]5/2 level (from the $j_{15/2}$ shell) after the band crossing.

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a.19. Superdeformation Studies in the Odd-Odd Nucleus ^{192}Tl (S. Fischer, M. P. Carpenter, R. V. F. Janssens, B. Crowell, R. G. Henry, I. Ahmad, T. L. Khoo, T. Lauritsen, D. Nisius, and B. Cederwall†)

The study of yrast and near-yrast structures of odd-odd nuclei to high spins is somewhat limited due to the complexity of the spectra resulting from the many proton-neutron couplings near the Fermi surface. In superdeformed nuclei, the number of available protons and neutrons near the Fermi surface is somewhat limited due to the presence of large-shell gaps which stabilize the nuclear shape. Nevertheless, a relatively small number of available neutron and proton configurations can lead to fragmentation of the SD intensity into a number of different bands. Two good examples of this phenomenon were found in ^{192}Tl and ^{194}Tl where the presence of six superdeformed bands were reported in both nuclei.[1,2]

We re-examined ^{192}Tl at Gammasphere using the ^{160}Gd(^{37}Cl,5n) reaction at 178 MeV to populate states in the superdeformed well of this nucleus. While our previous study on ^{192}Tl at ATLAS[2] was very successful, a number of questions remained which formed the basis of our objectives in this experiment: (1) obtain better γ-ray energies for the known transitions and identify higher spin members in each band; (2) determine how the bands feed the known yrast states in ^{192}Tl as well as determine the complete spectrum in coincidence with the SD bands; (3) look for M1 transitions connecting proposed signature partners; (4) and attempt to identify other excitations in the superdeformed well.

Analysis is underway and four of the six bands were confirmed. The reasons that two of the reported bands were not observed in this latest work is still under investigation. As of this time, no other superdeformed bands were identified in the data. Two of the confirmed SD bands have a constant moment of inertia and show indications of cross-talk between each other. This observation is not unexpected since the calculated M1 rates for the proposed configuration of the band, $\pi i_{13/2} \times \nu j_{15/2}$, indicate that M1 transitions linking the two SD bands should be observed.

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†Lawrence Berkeley National Laboratory.

[1]Y. Liang et al., Phys. Rev. C 46, R2136 (1992), [2]F. Azaiz et al., Phys. Rev. Lett. 66, 1030 (1991).

a.20. New Features of Superdeformed Bands in ^{194}Hg (R. V. F. Janssens, I. Ahmad, M. P. Carpenter, B. Crowell, R. G. Henry, T. L. Khoo, T. Lauritsen, B. Cederwall,* I. Y. Lee,* M. A. Deleplanque,* R. M. Diamond,* P. Fallon,* A. O. Machiavelli,* F. S. Stephens,* M. J. Brinkmann,† J. A. Becker,† L. P. Farris,† E. A. Henry,† J. R. Hughes,† M. A. Stoyer,† J. E. Draper,‡ C. Duyar,‡ E. Rubel,‡ W. Satula,§ I. Wiedenhoever,§ and R. Wyss§)

A striking difference between superdeformed (SD) nuclei near A = 190 and those in the other regions is the behavior of the dynamic moment of inertia $\Im^{(2)}$ with the rotational frequency $\hbar\omega$. While the $\Im^{(2)}$ patterns of the SD bands near A = 130 and A = 150 show pronounced variations, the majority of the SD bands near A = 190 display the same large, smooth increase of $\Im^{(2)}$ within the frequency range $0.15 < \hbar\omega < 0.40$ MeV. Current interpretations of this rise of $\Im^{(2)}$ within mean field theories invoke the gradual alignment of quasiparticles occupying high-N intruder orbitals in the presence of pair correlations. It is a direct consequence of these interpretations that, after the quasiparticle alignments take place, $\Im^{(2)}$ will exhibit a downturn with increasing $\hbar\omega$ toward the rigid-body value. Up to now, no downturn in $\Im^{(2)}$ for the SD bands in the A = 190 mass region was observed, raising some doubt as to our understanding of pair correlations and alignment effects at these large deformations.

An experiment was carried out at the 88-Inch Cyclotron facility of the Lawrence Berkeley Laboratory where excited states in ^{194}Hg were populated with the reaction ^{150}Nd(^{48}Ca,4n)^{194}Hg at a beam energy of 206 MeV. The gamma rays emitted in the reaction were detected with the Gammasphere detector array (32 detectors for this experiment).

Compared with previous work,[1] the three SD bands in ^{194}Hg were all extended to higher spins by two or three transitions. It is now possible to extend the dynamic moments of inertia up to frequencies larger than 0.4 MeV. In the strongest SD band, a change in the slope of $\Im^{(2)}$ with $\hbar\omega$ is noticeable for $\hbar\omega \sim 0.37$ MeV and, for the first time in this mass region, a clear turnover is present around $\hbar\omega = 0.43$ MeV. The characteristics of the two other SD bands are very similar. These results can be understood, at least qualitatively, in the framework of new, improved cranked-shell-model calculations where the monopole-pairing interaction was treated self-consistently by means of the Lipkin-Nogami method.

A second important result of this work relates to the possible presence of a higher-order symmetry in SD nuclei. The appearance of a regular staggering pattern in a SD band in ^{149}Gd was presented recently as possible evidence for a new symmetry term in the Hamiltonian which is invariant under a rotation by $\pi/2$. The increased resolving power obtained from high-fold coincidence data allowed us to determine the SD transition energies in ^{194}Hg with greater accuracy than in previous work and evidence for a staggering of the gamma-ray energies, similar to that observed for the SD band in ^{149}Gd, is observed in all three bands. There is at present no satisfactory detailed theoretical calculations explaining this observation.

This work was published.[2] Further experiments are planned in order to determine if the downbend in $\Im^{(2)}$ is present in other SD nuclei and if the above mentioned staggering is present as well.

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*Lawrence Berkeley Laboratory, †Lawrence Livermore Laboratory, ‡University of California-Davis, §Manne Siegbahn Institute, Stockholm, Sweden.

[1]M. A. Riley et al., Nucl. Phys. A512, 178 (1990), [2]B. Cederwall et al., Phys. Rev. Lett. 72, 3150 (1994).

a.21. Collectivity of High Spin States in ^{84}Zr (C. J. Lister, P. Chowdhury,* D. Blumenthal, B. Crowell, A. Aprahamian,† and T. Johnson†)

^{84}Zr is one of the most extensively studied of the A ~ 80 rotors, both from theoretical and experimental approaches.[1] It was predicted to be a good candidate to support superdeformation, and to show interesting spectroscopic properties including saturation of its shell-model space at lower spin.

We performed an experiment using Gammasphere in its early implementation phase.[2] The reaction of ^{29}Si on ^{58}Ni was used to strongly populate ^{84}Zr at high spin. Thin and thick targets were used to allow the extraction of transitional matrix elements at very high spin, and to allow a sensitive search for superdeformed states.

Data analysis is in progress. The large data set allowed us to extend the previously known bands considerably. Candidates for a staggered M1-band, found previously in ^{86}Zr, were located. To date, no evidence for superdeformed bands was found. Analysis was slowed by the relocation of all the participants in this experiment, but we hope to complete the lifetime analysis this year. This analysis has become especially topical, due to reported measurements of superdeformation in this region.

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*Wellesley College, †University of Notre Dame.

[1]A. A. Chishti et al., Phys. Rev. C 48, 2607 (1993) and references therein. [2]C. J. Lister, P. Chowdhury, and D. Vretenar, Proc. of Conf. on Perspectives for the Interacting Boson Model, World Scientific, 239 (1995).

B.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 its vicinity concentrated mainly on nuclei near A = 190, i.e. in the region where most of the superdeformation studies by the Argonne group are 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. This region is also one of the very few where the cranked shell model can be tested in the limit of oblate collective rotation. In fact, in some nuclei of this region, collective bands associated with prolate and oblate collective shapes were shown to coexist. Thus, the cranked shell model can be tested in both the prolate and oblate limits in a single nucleus. Recently, our studies concentrated on the Hg isotopes with A = 188-191 which involve mainly neutron excitations and on Pb nuclei with A = 192,195,196 where proton excitations turn out to be particularly intriguing. Indeed, sequences of M1 transitions were observed in these nuclei. Insight into the associated quasiparticle configurations was obtained not only from the usual level properties (spins, excitation energies etc..), but also from the detailed measurement of lifetimes.

The Fragment Mass Analyzer (FMA) is now fully operational and can be used in conjunction with 10 Compton-suppressed Ge detectors for spectroscopy studies in nuclei located far from the valley of stability. Experiments this year yielded results on ^{189,187}Pb, ^{179}Au, ^{181}Hg, ^{194,195,197}Po and ^{202,204}Rn. A common theme in these cases is shape coexistence. All projects at the FMA involve strong collaborations with outside users.

Finally, we list other aspects of the research program, many of which involve major efforts by collaborators from outside institutions. These include (1) the search for 2-octupole phonon excitations in ^{208}Pb, (2) the study of the decays of high-K isomers in ^{176}W, (3) the study of neutron-rich nuclei from the prompt radiation of fission fragments, (4) the study of quasiparticle excitations in neutron-rich Sn nuclei following complex heavy-ion-induced reactions involving the exchange of several nucleons between the target and the projectile, and (5) the study of shape-driving orbitals in Pt-Ir-Au nuclei through lifetime measurements.

b.1. Studies of Normal Deformation in ^{151}Dy (D. Nisius, R. V. F. Janssens, B. Crowell, I. Ahmad, M. P. Carpenter, R. G. Henry, T. L. Khoo, T. Lauritsen, P. Fallon,† B. Cederwall,† M. A. Deleplanque,† R. M. Diamond,† I. Y. Lee,† A. O. Machiavelli,† F. S. Stephens,† P. J. Daly,‡ Z. W. Grabowski,‡ R. M. Mayer,‡ and P. J. Twin§)

The wealth of data collected in the study of superdeformation in ^{151}Dy allowed for new information to be obtained on the normally deformed structures in this nucleus. At high spin several new yrast states have been identified for the first time. They were associated with single-particle excitations. Surprisingly, a sequence was identified with energy spacings characteristic of a rotational band of normal ($\beta_2 \sim 0.2$) deformation. The bandhead spin appears to be $15/2^-$ and the levels extend up to a spin of $87/2^-$. A clear backbend is present at intermediate spins. While a similar band based on a bandhead of 6^+ is known in ^{152}Dy, calculations suggest that this collective prolate band should not be seen in ^{151}Dy. In the experiment described earlier in this report that is aimed at determining the deformations associated with the SD bands in this nucleus and ^{152}Dy, the deformation associated with this band will be determined. This will provide further insight into the origin of this band.

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†Lawrence Berkeley Laboratory, ‡Purdue University, §Liverpool University, UK.

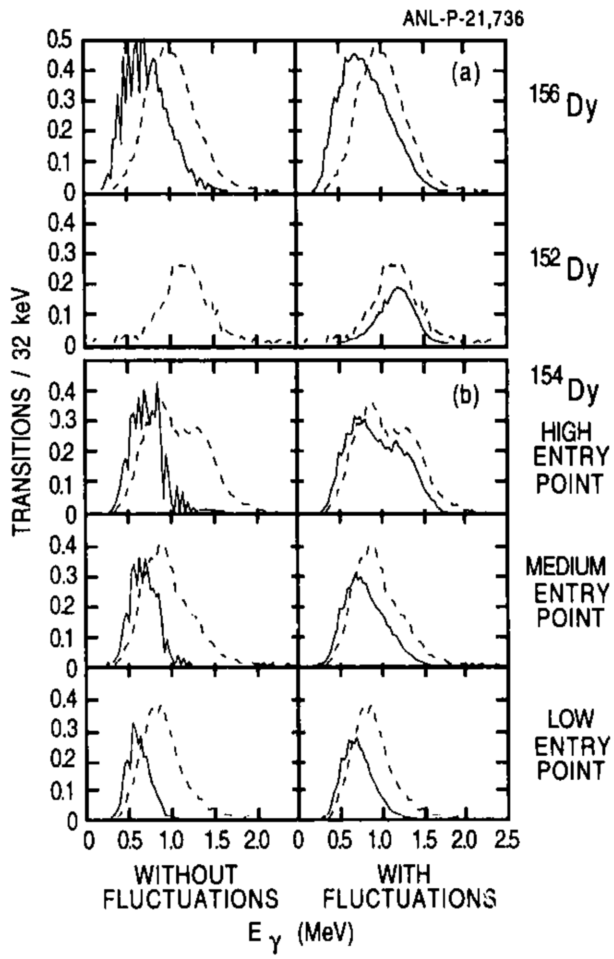

Fig. I-22. (a) Quasicontinuum E2 and γ spectra for the ^{152}Dy and ^{156}Dy nuclei at a beam energy of 160 MeV for ^{152}Dy and 155 MeV for ^{156}Dy [experimental results in dashed lines) and two types of calculations (solid lines) in the two columns (FTHF) and FTHF plus shape fluctuations, respectively]. (b) Same as for (a) for ^{154}Dy at three different beam energies (top panel 165 MeV, middle 155 MeV, and bottom panel row 148 MeV).

b.2. Numerical Simulations of the Cascades of the Nuclei ^{152,154,156}Dy with Self-Consistent Collective Strength Functions (T. L. Khoo, T. Lauritsen, V. Martin,*J. L. Egido*)

Mean-field theories predict phase transitions in nuclei, such as a transition from collective to oblate shapes. However, fluctuations in the finite nucleus smear out the transition, and it is an interesting problem in mesoscopic physics to search for a remnant signature of the phase transition. Temperature-dependent Hartree-Fock theory predicts that the collective-to-oblate phase transition boundaries occur in a domain that can be favorably probed in experiments in ^{152,154,156}Dy. These calculations were motivated by our past measurements of the quasicontinuum E2 spectra in these nuclei.

Using the results of temperature-dependent Hartree-Fock theory, we calculated gamma cascades and spectra in the above Dy nuclei. Spectra based on mean-field results do not reproduce the experimental results. However, inclusion of thermal fluctuations yield calculated E2 spectra which are in impressive agreement with experimental ones [see Figure I-22]. This study provides a clear signal for

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*Universidad Autónoma de Madrid, Spain.

the need of thermal fluctuations in the description of nuclei with thermal excitation energies 1-8 MeV above the yrast line. Another spectacular success of the theory is its ability to reproduce the E2 spectra observed in ^{154}Dy, which exhibits two broad peaks. This unique feature is obtained only when the γ cascades cross the prolate-oblate phase transition boundary. It occurs only in ^{154}Dy, when the initial angular momentum is sufficiently high. The overall agreement with experiment in all Dy nuclei and, particularly, the reproduction of the two-bump feature in ^{154}Dy may be interpreted as a signature of the persistence of a phase transition in a mesoscopic system.

The results were accepted for publication. Future work will concentrate on theoretical and experimental investigations of specific regions of spin and excitation energy in ^{154}Dy. We plan to continue our collaboration with the theoreticians in Madrid and we shall also analyze Gammasphere data on ^{154}Dy. Mutifold data will allow us to, for the first time, select specific regions of spin and excitation energy.

b.3. Gamma Spectrum Following Neutron Capture in ^{167}Er (D. Visser, T. L. Khoo, C. J. Lister, D. Blumenthal, R. G. Henry, T. Lauritsen, I. Ahmad, M. P. Carpenter, B. Crowell, R. V. F. Janssens, D. Nisius, J. L. Durell,† W. R. Phillips,† J. A. Shannon,† B. J. Varley,† R. Casten,‡ and R. Gill‡)

Statistical decay from a highly excited state samples all the lower-lying states and, hence, provides a sensitive measure of the level density. Pairing has a major impact on the level density, e.g. creating a pair gap between the 0- and 2-quasiparticle configurations. Hence the shape of the statistical spectrum contains information on pairing, and can be used to provide information on the reduction of pairing with thermal excitation energy. For this reason, we measured the complete spectrum of γ rays following thermal neutron capture in ^{167}Er. The experiment was performed at the Brookhaven reactor using Compton-suppressed Ge detectors from TESSA. The spectrum, which was corrected for detector response and efficiency, reveals primary (first-step, high-energy) transitions up to nearly 8 MeV, secondary (last-step, lower-energy) transitions, as well as a continuous statistical component (see Figure I-23). Effort was expanded to identify all lines from contaminant sources and an upper limit of 5% was tentatively set for their contributions. The spectral shape of the statistical spectrum will be compared with theoretical spectra obtained from a calculation of pairing which accounts for a stepwise reduction of the pair correlations as the number of quasiparticles increases (see I.B.a.1.). The primary lines which decay directly to the near-yrast states will also be used to deduce the level densities.

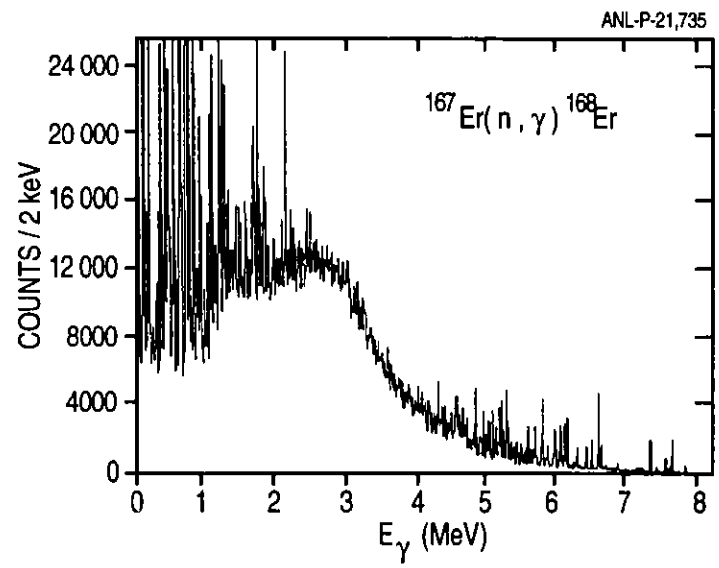

Fig. I-23. Gamma spectrum following thermal neutron capture in ^{167}Er.

γ-γ matrices of the data were also constructed. The aim here is to construct a level scheme for ^{168}Er which should be complete up to perhaps 3 MeV. These data will also test published level schemes which were constructed from singles data using the Ritz combination principle.

†University of Manchester, United Kingdom, ‡Brookhaven National Laboratory.

b.4. High-K Isomers in ^{176}W and Mechanisms of K-Violation (B. Crowell, R. V. F. Janssens, D. J. Blumenthal, C. J. Lister, T. L. Khoo, I. Ahmad, M. P. Carpenter, D. Gassmann, R. G. Henry, T. Lauritsen, Y. Liang, D. Nisius, F. Soramel, I. G. Bearden, P. Chowdhury,* and S. J. Freeman†)

K-isomers are states in deformed nuclei whose γ-decay is hindered by selection rules involving K, the projection of the angular momentum along the axis of symmetry of the nucleus. Previous work with the Argonne Notre Dame BGO Array delineated the existence of two K-isomers in ^{176}W, one of which had a very unusual pattern of decay. A short description of this work was published as a letter,[1] and a more complete account is being readied for submission. These results provided evidence that quantum-mechanical fluctuations in the nuclear shape may be responsible for some of the observed K-violating transitions.

In addition, hints were present in the data of the existence of another K-isomer with an even higher spin. An experiment was performed in September 1994 to observe this isomer, using the reaction ^{50}Ti(^{130}Te,4n), and a technique in which recoiling ^{176}W nuclei were created 17-cm upstream of the center of the array and caught on a Pb catcher foil at the center. Intense (~ 3 pnA) beams of ^{130}Te were supplied by the ECR source using a new sputtering technique. The recoil-shadow geometry was highly successful at removing the background from non-isomeric decays, allowing the weakly populated K-isomers to be detected cleanly. In addition, the availability of pulsed beams from ATLAS and the timing data from the BGO array provided a second technique for isolating the decays of interest, by selecting events in which a given number of BGO detectors fired between beam pulses. This method was used in the previous experiment, and was also applied in this experiment as a second level of selection. As a result, gamma-ray transitions were detected in the present experiment with intensities as small as ~ 0.02 % of the ^{176}W reaction channel.

The existence of the new isomer was confirmed, and a partial level-scheme was constructed. A proposal to study this isomer at Gammasphere was accepted. The Gammasphere experiment should provide complimentary data allowing the construction of a definitive level-scheme and the assignment of spins and parities to the states involved. The information on the new isomer may help to test the models of shape fluctuations employed in our previous work.

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*Wellesley College, †Schuster Laboratory, Manchester, United Kingdom.
[1]B. Crowell et al., Phys. Rev. Lett. 72, 1164 (1994).

b.5. Collectivity of Dipole Bands in ^{196}Pb (M. P. Carpenter, Y. Liang, R. V. F. Janssens, I. Ahmad, I. G. Bearden, R. G. Henry, T. L. Khoo, T. Lauritsen, D. Nisius, E. F. Moore,† P. J. Daly,‡ M. W. Drigert,§ B. Fornal,‡ U. Garg,¶ Z. W. Grabowski,‡ H. L. Harrington,† R. H. Mayer,‡ W. Reviol,¶ and M. Sferrazza‡)

The region of nuclei with mass ~ 190 was studied extensively over the last few years following the discovery of superdeformation in ^{190}Hg. More recently, considerable interest in the neutron-deficient Pb isotopes developed with the discovery of a number of bands at high spin connected by dipole transitions in both even $^{192-200}$Pb and odd $^{197-201}$Pb nuclei. The majority of the dipole bands are regular in character (i. e. transition energies increase smoothly with spin) while the remaining bands are referred to as irregular in character, due to the fact that the transition energies do not increase smoothly with spin. The properties of the dipole bands were interpreted in terms of high-K, moderately-deformed oblate states built on configurations involving high-j, shape-

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†North Carolina State University and Triangle Universities Nuclear Research Laboratory, ‡Purdue University, §Idaho National Engineering Laboratory, ¶University of Notre Dame.
[1]J. R. Hughes et al., Phys. Rev. C 47, R1337 (1993).

driving quasiproton excitations coupled to rotation-aligned quasineutrons. It was suggested that the difference between the regular and irregular dipole sequences is related to the deformation where the irregular sequences are thought to be less collective than their regular counterparts.

In order to test this assertion, we performed an experiment to measure the lifetimes in the dipole bands of ^{196}Pb utilizing the Doppler Shift Attenuation Method (DSAM). From our previous work,[1] three regular bands and one irregular band were identified in this nucleus. Excited states in ^{196}Pb were populated using the reaction $^{170}Er(^{30}Si,4n)$ with an ATLAS beam of 142 MeV, and data were taken using the Argonne Notre Dame BGO γ-ray Facility. The data were of sufficient quality to allow for a complete lineshape analysis to be performed on transitions in the irregular sequence and one of the regular dipole bands. The lifetime results show that the B(M1) values in the two bands are very similar with average values of ~ 1.5 W.u. (see Fig. I-24).

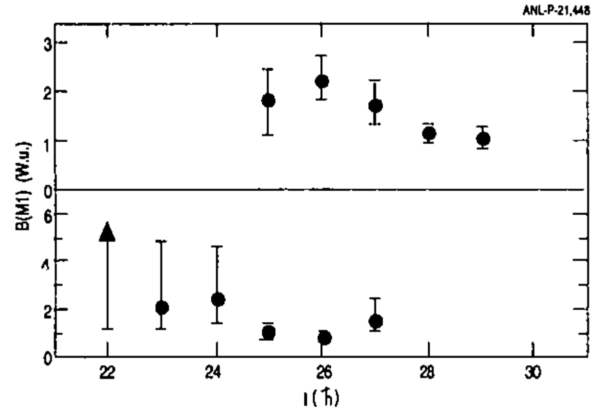

Fig. I-24. Experimental B(M1) values for band 3 (top), and band 2 (bottom) in ^{196}Pb.

From these results, we concluded that the collectivity in the two measured bands is nearly the same, which contradicts previous claims suggesting that the irregular sequences were less deformed than the regular dipole bands. This led us to conclude that the irregular bands are indeed rotational structures based on configurations with some degree of signature splitting, which undergo quasineutron alignments in the observed frequency range. A paper on this work was published recently.

b.6. Search for the Two-Phonon Octupole Vibrational State in ^{208}Pb

(D. J. Blumenthal, W. Henning, R. V. F. Janssens, T. L. Khoo, I. Ahmad, M. P. Carpenter, B. Crowell, D. Gassman, R. G. Henry, T. Lauritsen, C. J. Lister, D. Nisius, E. F. Moore,† S. J. Sanders,‡ H. Amro,† and M. W. Drigert§)

We performed an experiment to search for the two-phonon octupole vibrational state in ^{208}Pb. Thick targets of ^{208}Pb, ^{209}Bi, $^{58,64}Ni$, and ^{160}Gd were bombarded with 1305 MeV beams of ^{208}Pb supplied by ATLAS. Gamma rays were detected using the Argonne-Notre Dame BGO gamma-ray facility, consisting of 12 Compton-suppressed germanium detectors surrounding an array of 50 BGO scintillators. We identified some 30 known gamma rays from ^{208}Pb in the spectra gated by the $5^- \rightarrow 3^-$ and $3^- \rightarrow 0^+$ transitions in ^{208}Pb. In addition, after unfolding these spectra for Compton response, we observed broad coincident structures in the energy region expected for the 2-phonon states. Furthermore, we confirmed the placement of a 2485 keV line observed previously in ^{207}Pb and find no evidence consistent with the placement of this line in ^{208}Pb.

We are currently in the process of investigating the origin of the broadened lines observed in the spectra, extracting the excitation probability of states in ^{208}Pb, and determining the relative probability of mutual excitation and neutron transfer in this reaction. An additional experiment is also being performed to collect much higher statistics germanium-germanium coincidence data for the thick ^{208}Pb target.

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†North Carolina State University and Triangle Universities Nuclear Laboratory,
‡University of Kansas, §Idaho National Engineering Laboratory.

b.7. Triaxial Shapes in the Ground States of Even-Even Neutron-Rich Ru Isotopes (I. Ahmad, C. J. Lister, L. R. Morss,* K. L. Nash,* C. W. Williams,* J. A. Shannon,† W. R. Phillips,† J. L. Durell,† B. J. Varley,† W. Urban,† C. J. Pearson,† M. Bentaleb,‡ E. Lubkiewicz,‡ and N. Schulz‡)

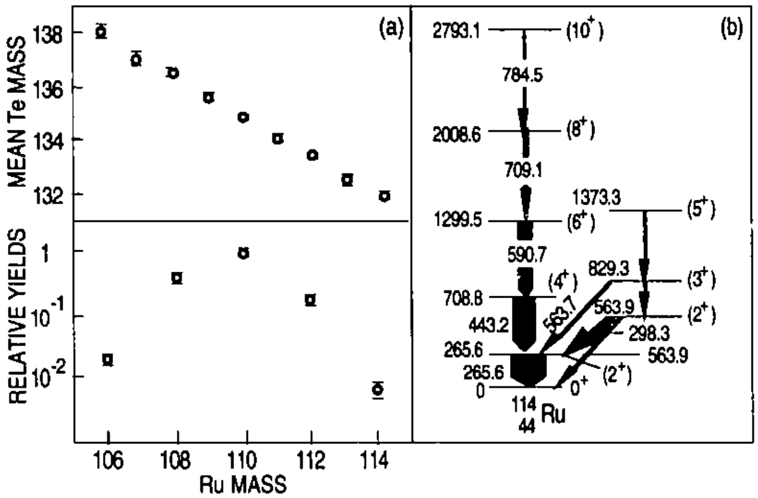

Fig. I-25. (a) Mean mass of Te complementary fragments in coincidence with known transitions in $^{106-112}$Ru and proposed transitions in ^{113}Ru and ^{114}Ru. The smooth trend in the data points is the basis of the assignment of γ-ray lines to ^{113}Ru and ^{114}Ru. (b) Partial decay scheme for ^{114}Ru. The numbers on the levels give excitation energies in keV. (c) Relative yields of prompt γ-ray emitting Ru isotopes.

Partial level schemes for ^{108,110,112}Ru, and ^{114}Ru about which nothing was previously known, were determined from the measurement of prompt, triple-gamma coincidences in ^{248}Cm fission fragments. A 5-mg ^{248}Cm source, mixed with 65-mg KCl and pressed in the form of a 7-mm diameter pellet, was used for the experiment. Prompt γ rays emitted from the fission fragments were detected with the Eurogam array at Daresbury, which at that time consisted of 45 Compton-suppressed Ge detectors and 5 LEPS spectrometers. Transitions in Ru were identified by gating on γ rays in the complementary Te fragments. Figure I-25 shows the technique used to identify the previously unknown transitions in ^{114}Ru and its partial level scheme. High spin states up to spin 10 ħ were observed and the γ-ray branching ratios were determined. The ratios of electric quadrupole transition probabilities deduced from the experimental branching ratios were found to be in good agreement with the predictions of a simple model of rigid triaxial rotor. Our analysis shows that gamma deformation in Ru isotopes is increasing with the neutron number and the gamma value for ^{112}Ru and ^{114}Ru is ~ 25 degrees. This is one of the highest gamma values encountered in nuclei, suggesting soft triaxial shapes for ^{112}Ru and ^{114}Ru. The results of this investigation were published.

*Chemistry Division, ANL, †University of Manchester, United Kingdom, ‡CRN, Strasbourg, France.

b.8. Level Structures of Neutron-Rich Xe Isotopes (I. Ahmad, C. J. Lister, L. R. Morss,* K. L. Nash,* C. W. Williams,* M. Bentaleb,† E. Lubkiewicz,† N. Schulz,† J. L. Durell,‡ F. Liden,‡ C. J. Pearson,‡ W. R. Phillips,‡ J. Shannon,‡ and B. J. Varley‡)

The level structures of neutron-rich Xe isotopes were determined by observing prompt gamma-ray coincidences in ^{248}Cm fission fragments. A 5-mg ^{248}Cm, in the form of ^{248}Cm-KCl pellet, was placed inside Eurogam array which consisted of 45 Compton-suppressed Ge detectors and 5 Low-Energy Photon Spectrometers. Transitions in Xe isotopes were identified by the appearance of new peaks in the γ-ray spectra obtained by gating on the gamma peaks of the complementary Mo fragments.

*Chemistry Division, ANL, †CRN, Strasbourg, France, ‡University of Manchester, United Kingdom.

Using a technique developed in our earlier investigations, transitions in the previously unknown nuclei ^{143}Xe and ^{144}Xe were identified. Figure I-26 shows level schemes of ^{143}Xe and ^{144}Xe. In ^{144}Xe, the ground state band was identified up to spin 10 $\hbar$. The absence of E1 transitions in ^{144}Xe suggests that this nucleus does not have large octupole correlations, which is in disagreement with theoretical predictions. In ^{143}Xe, a parity doublet with spin 5/2 was identified suggesting moderate octupole collectivity.

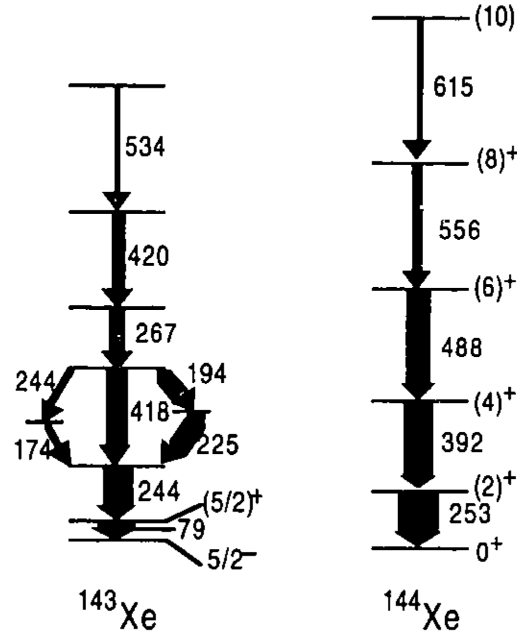

Fig. I-26. Level schemes of ^{143}Xe and ^{144}Xe deduced from the analysis of the ^{248}Cm fission data.

b.9. Lifetimes in Neutron-Rich Nd Isotopes Measured by Doppler Profile Method (I. Ahmad, C. J. Lister, L. R. Morss,* K. L. Nash,* C. W. Williams,* A. G. Smith,† W. R. Phillips,† J. L. Durell,† W. Urban,† B. J. Varley,† C. J. Pearson,† J. A. Shannon,† M. Bentaleb,‡ E. Lubkiewicz,‡ and N. Schulz‡)

Lifetimes of the rotational levels in neutron-rich even-even Nd isotopes were deduced from the analysis of the Doppler broadened line shapes. The experiment was performed at Daresbury with the Eurogam array, which at that time consisted of 45 Compton-suppressed Ge detectors and 5 Low-Energy Photon Spectrometers. The source was in the form of a 7-mm pellet which was prepared by mixing 5-mg ^{248}Cm and 65-mg KCl and pressing it under high pressure. Events for which three or

*Chemistry Division, ANL, †University of Manchester, United Kingdom, ‡CRN, Strasbourg, France.

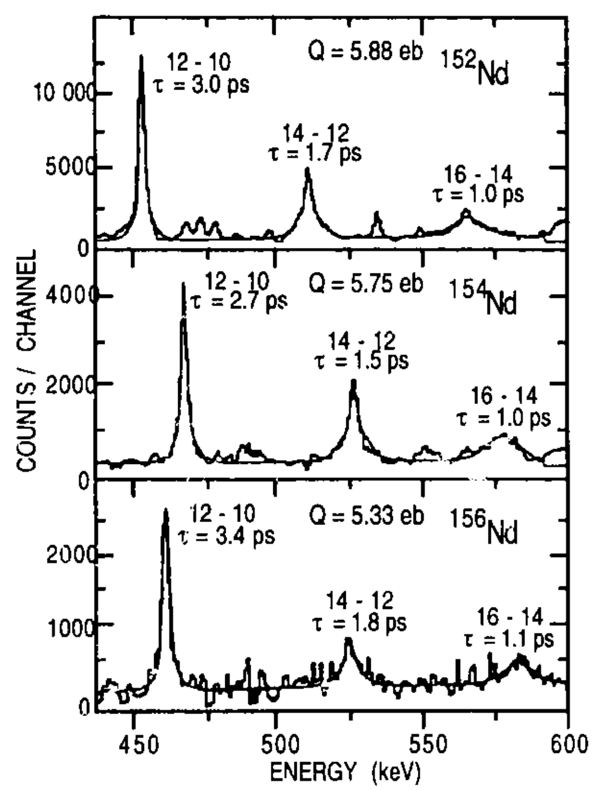

Fig. I-27. Line shapes of the γ-ray energy spectra of $^{152,154,156}Nd$. The fits (smooth lines) are superimposed on the data (histograms). Each photopeak is marked with the spins of the initial and final levels of the decay as well as with the mean lifetime (τ) of the initial level. The resulting transition electric quadrupole moments (Q) are also given.

more detectors fired were used to construct a cubic data array whose axes represented the γ-ray energies and the contents of each channel the number of events with that particular combination of γ-ray energies. From this cubic array, one-dimensional spectra were generated by placing gates on peaks on the other two axes. Gamma-ray spectra of even-even Nd isotopes were obtained by gating on the transitions in the complimentary Kr fragments. The gamma peaks de-exciting states with $I \geq 12\ \hbar$ were found to be broader than the instrumental line width due to the Doppler effect. The line shapes of the γ-ray peaks were fitted separately with a simple model for the feeding of the states and assuming a rotational band with constant intrinsic quadruple moment and these are shown in Fig. I-27. The quadrupole moments thus determined were found to be in good agreement with the quadrupole moments measured previously for lower spin states. Because of the success of this technique for the Nd isotopes, we intend to apply this technique to the new larger data set collected with the Eurogam II array. The results of this study were published.

b.10. Lifetimes of High-Spin States in ^{162}Yb (M. P. Carpenter, R. V. F. Janssens, R. G. Henry, T. L. Khoo, T. Lauritsen, D. Nisius, M. J. Fitch,† C.-H. Yu,† D. M. Cullen,† R. W. Gray,† and X. H. Wang†)

A measurement on lifetimes of high-spin states in the yrast and near-yrast rotational bands in ^{162}Yb was carried out at ATLAS in order to determine the evolution of collectivity as a function of angular momentum using the ^{126}Te(^{40}Ar,4n)^{162}Yb reaction at 170 MeV. Previous lifetime measurements in the ^{164,166,168}Yb isotopes[1] showed a dramatic decrease in the transition quadrupole moment Q_t with increasing spin. It was suggested that this decrease in Q_t is brought about by the rotationally-induced deoccupation of high-j configurations, mainly $i_{13/2}$ neutrons. If this interpretation is correct, the heavier isotopes should have a larger decrease in Q_t than the lighter mass nuclides due to the position of the Fermi surface in the $i_{13/2}$ subshell. Indeed, ^{160}Yb does not show a clear decrease in Q_t at high spin. No high spin lifetime information exists for ^{162}Yb, thus this experiment fills the gap of measured Q_t's in the light Yb series. The data is currently being analyzed.

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†Nuclear Structure Laboratory, Univ. of Rochester.
[1]C.-H. Yu et al., Phys. Rev. C, in press.

b.11. Measurement of Lifetimes of High Spin States in the N = 106 Nuclei ^{183}Ir and ^{182}Os (I. Ahmad, D. Blumenthal, M. P. Carpenter, B. Crowell, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, D. Nisius, R. Kaczarowski,* U. Garg,† R. Lehmkuhl,† S. Naguleswaran,† B. Prause,† G. Smith,† and J. C. Walpe†)

Lifetimes of high spin states in the isotones ^{183}Ir and ^{182}Os were measured using the Notre Dame plunger device in conjunction with the Argonne Notre Dame γ-ray facility. The aim of these measurements was to determine the deformation-driving properties of the $h_{9/2}$ proton intruder orbital by comparing the values of the intrinsic quadrupole moments in the ground state bands in the odd-mass Ir nucleus and the even-even Os core. Levels in these nuclei were populated by the ^{150}Nd (^{37}Cl,4n) and ^{150}Nd (^{36}S,4n) reactions using a ^{37}Cl beam of 169 MeV and 164-MeV ^{36}S beam. The ^{150}Nd target was 0.9-g/cm^2 thick and was prepared by evaporating enriched ^{150}Nd onto a stretched 1.5-mg/cm^2 gold foil. The target was covered with a layer of a 60-µg/cm^2 Au to prevent its oxidation. Gamma-ray spectra were accumulated for approximately 4 hours for each target-stopper distance. Data were collected for 20 target-stopper distances ranging from 16 µm to 10.4 mm. Preliminary analysis indicates that it will be possible to extract the lifetimes of the levels in the yrast bands up to and including part of the backbending region with sufficient accuracy. Detailed analysis of the data is in progress.

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*Soltan Institute for Nuclear Studies, Swierk, Poland, †University of Notre Dame.

b.12. Lifetimes of High-Spin States in $^{180\text{-}184}Pt$ (M. P. Carpenter, I. Ahmad, B. Crowell, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, U. Garg,* S. Naguleswaran,* B. Prause,* G. Smith,* J. C. Walpe,* R. Kaczarowski,† W. Mueller,‡ W. Reviol,‡ L. L Riedinger,‡ and E. F. Moore,§)

Over the past few years, lifetimes were measured, using the recoil distance method, to investigate shape-coexistence and shape transitions in the even mass $^{182\text{-}186}Pt$ isotopes. In all three cases, one observes a sharp increase in the transition quadrupole moment, Q_t, at low frequencies followed by a rapid and significant decline in the backbending region. It was shown that the initial increase in the Q_t can be explained in terms of the mixing at low spins of two bands of very different deformation, and the decline in the backbending region is brought about by mixing between the ground and a two-quasiparticle band.[1] No lifetime information exists for these nuclei above the backbend, and there is some contention whether or not the backbend is due to the alignment of $h_{9/2}$ protons, $i_{13/2}$ neutrons or the near simultaneous alignment of both. Nilsson-Strutinsky calculations indicate very different shapes for the nuclei after the backbend, depending on which orbitals align. Thus, lifetime information on the states above the backbend should help determine which interpretation is correct.

In order to determine the lifetimes of states in the even mass $^{180\text{-}184}Pt$ nuclei above the backbend, we performed a recent experiment at Gammasphere using a ^{64}Ni beam on Pb backed Sn targets in order to populate the nucleus of interest via a 4n reaction. At the time of the experiment, thirty-six Ge detectors were available for use in Gammasphere and approximately 100×10^6 3-fold and higher events were taken for each nucleus. Currently, angle-sorted matrices were created from the data, and spectra representing the ground bands show well developed lineshapes for transitions above the backbend. A full lineshape analysis of the data will begin shortly.

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*University of Notre Dame, †Soltan Institute for Nuclear Studies, Swierk, Poland.
‡University of Tennessee, §North Carolina State University,
[1]J. C. Walpe, Ph.D. Thesis, University of Notre Dame.

b.13. Gamma-Ray Spectroscopy of Neutron-Rich Products of Heavy-Ion Collisions (M. P. Carpenter, R. V. F. Janssens, I. Ahmad, R. G. Henry, T. L. Khoo, T. Lauritsen, Y. Liang, C. T. Zhang,* R. H. Mayer,* P. Bhattacharyya,* D. Nisius, I. G. Bearden, L. G. Richter,* M. Sferrazza,* Z. W. Grabowski,* P. J. Daly,* B. Fornal,‡ R. Broda,‡ and J. Blomqvist§)

Thick-target $\gamma\gamma$ coincidence techniques are being used to explore the spectroscopy of otherwise hard-to-reach neutron-rich products of deep-inelastic heavy ion reactions. Extensive $\gamma\gamma$ coincidence measurements were performed at ATLAS using pulsed beams of ^{80}Se, ^{136}Xe, and ^{238}U on lead-backed $^{122,124}Sn$ targets with energies 10-15% above the Coulomb barrier. Gamma-ray coincidence intensities were used to map out yield distributions with A and Z for even-even product nuclei around the target and around the projectile. The main features of the yield patterns are understandable in terms of N/Z equilibration. We had the most success in studying the decays of yrast isomers. Thus far, more than thirty new µs isomers in the $Z = 50$ region were found and characterized. Making isotopic assignments for previously unknown γ-ray cascades proves to be one of the biggest problems. Our assignments were based a) on rare overlaps with radioactivity data, b) on the relative yields with different beams, and c) on observed cross-coincidences between γ rays from light and heavy reaction partners. However, the primary products of deep inelastic collisions often are sufficiently excited for subsequent neutron evaporation, so $\gamma\gamma$ cross-coincidence results require careful interpretation.

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*Purdue University, ‡ INP, Cracow, Poland, §Royal Institute of Technology, Stockholm, Sweden.

Our most extensive results are for the eight semi-magic tin nuclei from ^{119}Sn to ^{126}Sn, where $(\nu h_{11/2})^n$, seniority 2 and 3, 10^+ and $27/2^-$ isomers and their decays were identified and characterized. The B(E2) values of the isomeric transitions between the $(\nu h_{11/2})^n$ states reflect the $\nu h_{11/2}$ subshell occupation, and the experimental values pinpoint the half-filling of this subshell very close to ^{123}Sn, where the observed B(E2) is less than 0.002 Weisskopf units (see Figures I-28 and I-29). Recent results for odd-A nuclei match up excellently with those obtained previously for even-A tin isotopes, and they reinforce and refine the conclusions about the $\nu h_{11/2}$ subshell filling, about the differences between $h_{11/2}$ neutrons and protons, and about the enhancement of the neutron effective charge towards the middle of the N = 50-82 major shell. The $(\nu h_{11/2})^n$ n = 3 configuration assignments for the $23/2^-$ and $27/2^-$ yrast levels in odd-A Sn nuclei could be made with unusual confidence because the experimental excitation energies are correctly predicted with high precision (within a few keV) by fractional parentage techniques making use of the accurately known ground-state masses of tin isotopes.

In other analyses of the same experimental data sets, new yrast cascades and isomers are being studied in odd-A Sb nuclei from ^{121}Sb to ^{129}Sb, in odd-A In nuclei from ^{115}In to ^{123}In and in a series of N = 80 isotones including ^{134}Xe and ^{136}Ba.

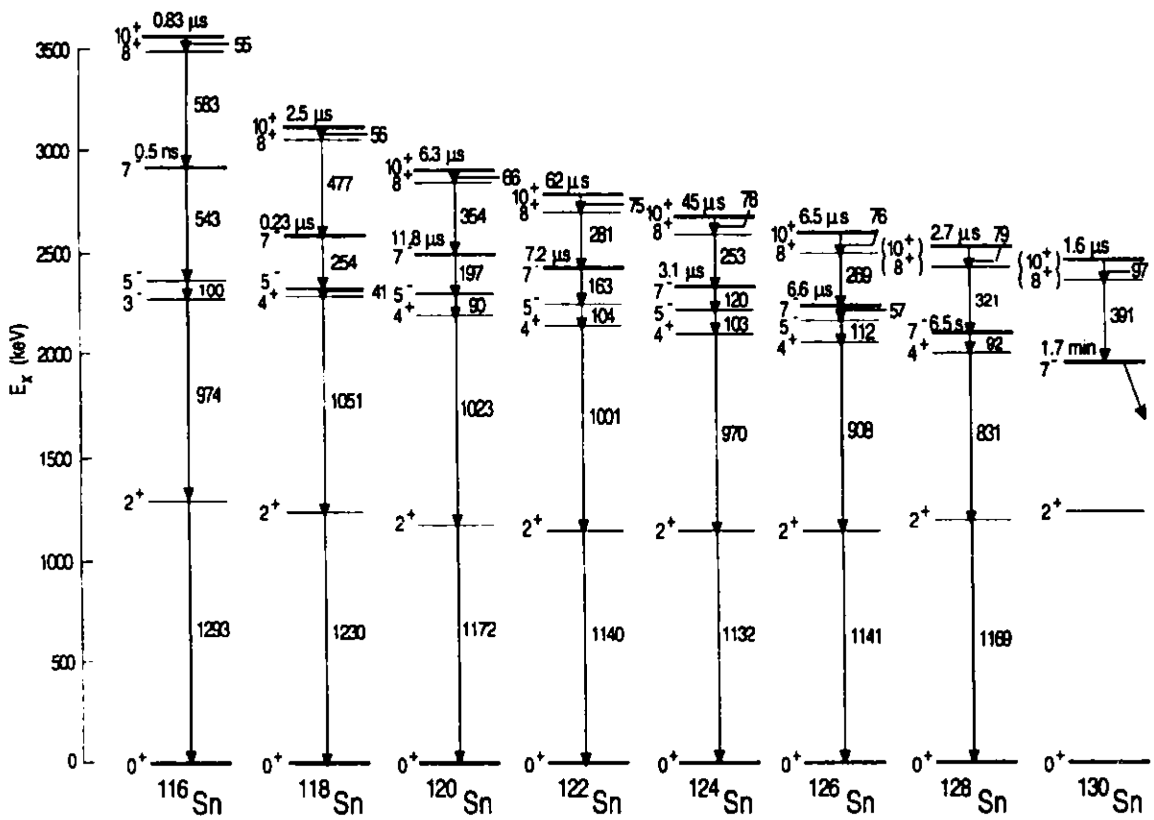

Fig. I-28. Energy systematics of even-A tin isotopes, showing the main decay pathways of the 10^+ isomers.

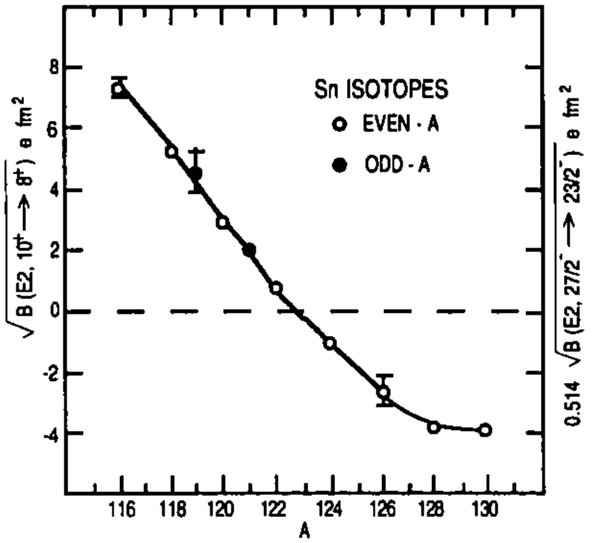

Fig. I-29. Measured E2 transition amplitudes between 10^+ and 8^+ of the $(\nu h_{11/2})^n$ $v = 2$ states in even-A nuclei as well as between $27/2^-$ and $23/2^-$ of the $(\nu h_{11/2})^n$ $v = 3$ states in odd-A tin nuclei. Where error bars are not shown they lie within the plotted point. The solid line is drawn through the points to guide the eye.

b.14. Production of Actinide Nuclei by Multi-Nucleon Transfer (T. Lauritsen, I. Ahmad, M. P. Carpenter, B. Crowell, R. G. Henry, R. V. F. Janssens, T. L. Khoo, D. Nisius, P.A. Butler,† J. F. C. Cocks,† G. D. Jones,† and J. F. Smith†)

Multi-nucleon transfers have increasingly allowed us to reach parts of the nuclear chart where regular compound nuclear reactions are prohibited. The interesting region of Ra and Rn, where a rich tapestry of nuclear structure manifests itself, is now accessible using this technique of deep inelastic scattering. In particular, these nuclei are predicted to lie at the onset of octupole deformation and the region is rich in examples of shape coexistence. There are several theoretical predictions of nuclear structure of these nuclei that have not been experimentally tested. Moreover, there is serious disagreement among these theories.

We used a beam of ^{136}Xe at 720 MeV from ATLAS on a target of ^{232}Th to produce a range of Rn isotopes, with a mass from 220 to 224, and Ra isotopes with masses greater than 222. The beam energy, target and beam were selected carefully to enhance the cross-section for production of these nuclei and reduce the Doppler broadening of the gamma rays that were observed in the Argonne Notre Dame gamma-ray facility. The 12 germanium detectors of this array allowed the observation of gamma-gamma coincidences. The inner ball of 50 BGO detectors allowed us to record the multiplicity and sum-energy information for each event. The latter should permit us to determine the entry region in the products of the transfer reaction. We had four successful days of beam-time, when we collected in excess of 8×10^7 events. Data analysis is in progress at the University of Liverpool. A complete set of spectroscopic information on the yrast structure of the many nuclei produced in this reaction is being extracted.

†Oliver Lodge Laboratory, University of Liverpool, United Kingdom.

b.15. Coulomb Excitation of Radioactive ^{79}Rb (C. J. Lister, D. Blumenthal, C. N. Davids, S. Fischer, R. V. F. Janssens, M. P. Carpenter, and R. Gill*)

The technical challenges expected in experiments with radioactive beams can already be explored by using ions produced in primary reactions. In addition, the re-excitation of these ions by Coulomb excitation allows a sensitive search for collective states that are well above the yrast line.

*Brookhaven National Laboratory.

We are building an experiment to study Coulomb excitation of radioactive ions which are separated from beam particles by the Fragment Mass Analyzer. An array of gamma detectors will be mounted at the focal plane to measure the gamma radiation following re-excitation. Five Compton-suppressed Ge detectors and five planar LEPS detectors will be used. The optimum experiment of this type appears to be the study of ^{79}Rb following the ^{24}Mg (^{58}Ni,3p) reaction. We calculate that about 5×10^5 ^{79}Rb nuclei/second will reach the excitation foil. This rubidium isotope was selected for study as it is strongly produced and is highly deformed, so easily re-excited. The use of a ^{58}Ni re-excitation foil offers the best yields. After re-excitation the ions will be subsequently transported into a shielded beamdump to prevent the accumulation of activity.

This experiment will allow us to explore many issues: count rates which are small compared to ambient backgrounds; "polluted" beams of all A = 79 isobars; removal of activity of the beam particles, etc. It will allow us to estimate more reliably what Coulomb excitation experiments will be possible in the future with beams of comparable or weaker intensity.

Location of non-yrast collective states are of considerable interest. These A ~ 80 nuclei are highly deformed and shell stabilized. As such they are closely related to superdeformed nuclei. The locationof collective "beta" and "gamma" bands reflects the stiffness of these deformed potentials, which is not yet established, but is of considerable general interest.

b.16. Conversion Electron Spectroscopy at the FMA Focal Plane: Decay Studies of Proton-Rich N ~ 82 Nuclei (D. Nisius, R. V. F. Janssens, I. Ahmad, B. Crowell, M. P. Carpenter, C. N. Davids, D. Henderson, R. G. Henry, R. Hermann, T. L. Khoo, T. Lauritsen, H. Penttilä, P. Bhattacharyya,‡ P. J. Daly,‡ Z. W. Grabowski,‡ R. H. Mayer,‡ L. Richter,‡ and C. T. Zhang‡)

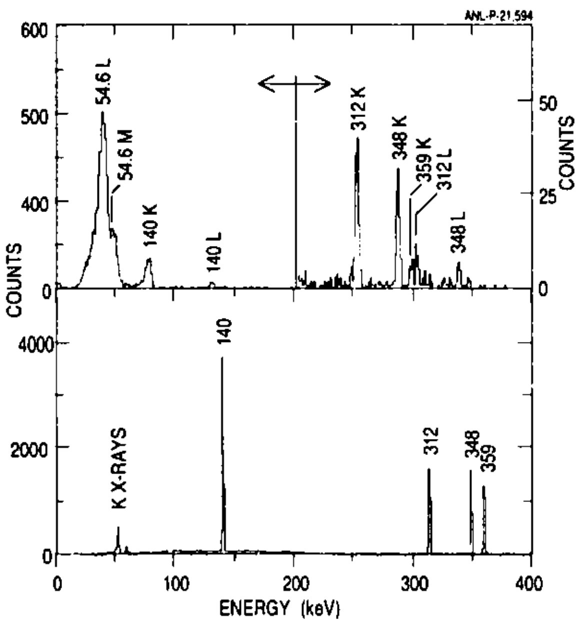

Fig. I-30. Mass gated conversion electron (top) and γ-ray (bottom) spectra for A = 152. All peaks belong to the ^{152}Yb nucleus. The two lowest energy peaks in the electron spectrum are the L and M conversion lines for the $10^+ \rightarrow 8^+$ transition, which escaped detection in previous γ-ray measurements.

The FMA has proven to be an ideal instrument for the detailed study of the decay of microsecond isomers behind the focal plane following mass selection. In reactions leading to the population of nuclei with isomeric lifetimes longer than their flight time through the device, decay gamma rays and conversion electrons can be detected in an environment free from the backgrounds of prompt radiation and delta electrons. This was a very successful technique to study proton $(h_{11/2})^n$ seniority isomers in nuclei with Z > 64 and N ~ 82.

Since isomeric decay gamma rays are emitted isotropically, conversion electrons are essential for the assignment of multipolarities in these nuclei. Furthermore, the low-energy transitions that depopulate isomeric states are typically highly converted and can escape gamma-ray detection, but they can be identified by their conversion electrons.

An experiment was performed with the reaction ^{96}Ru + 250 MeV ^{58}Ni $\rightarrow$ ^{154}Hf* in order to populate the seniority isomers in ^{151,152}Yb. The

‡Purdue University.

recoiling ions were mass separated and then brought to rest in a catcher foil behind the FMA focal plane where the subsequent decay gamma rays and electrons were detected by two large Ge detectors and two Si PIN diodes, respectively. In ^{152}Yb, multipolarities were determined for all yrast transitions below the 10^+ isomer (excluding the $2^+ \rightarrow 0^+$, 1531 keV transition). Also, the low-energy transitions de-exciting the seniority-three $27/2^-$ state in ^{151}Yb and the seniority-two 10^+ state in ^{152}Yb were identified for the first time. In the electron spectra the isomeric transitions were determined to have energies of 57 ± 2 keV and 54.6 ± 1.0 keV in ^{151}Yb and ^{152}Yb, respectively. A paper discussing our results is being prepared for publication (see Fig. I-30).

b.17. Observation of High Spin States in ^{179}Au (M. P. Carpenter, I. Ahmad, D. J. Blumenthal, L. Conticchio, B. Crowell, C. N. Davids, D. J. Henderson, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, D. Nisius, H. Penttilä, W. F. Mueller,‡ C. R. Bingham,‡ W. Reviol,‡ L. L. Riedinger,‡ J. D. Richards,‡ B. H. Smith,‡ B. E. Zimmerman,‡ W. C. Ma,§ and H.-Q. Jin,¶)

As part of a current study on the properties of the $\pi\, i_{13/2}$ intruder state in the A = 175-190 region, we conducted an experiment at ATLAS to observe high spin states in ^{179}Au utilizing the reaction ^{144}Sm(^{40}Ar,p4n) at beam energies of 207 MeV and 215 MeV. To aid in the identification of ^{179}Au, and to filter out the large amount of events from fission by-products, the Fragment Mass Analyzer was utilized in conjunction with ten Compton-suppression germanium detectors. In total, 11×10^6 γ-γ and 4×10^5 γ-recoil events were collected. By comparing γ rays in coincidence with an A = 179 recoil mass gate and γ rays in coincidence with Au K_α and K_β X-rays, ten γ rays were identified as belonging to ^{179}Au. Based on γ-ray coincidence relationships and on comparisons with neighboring odd-A Au nuclei, we constructed a tentative level scheme and assigned a rotational-like sequence to the $\pi\, i_{13/2}$ proton configuration.

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‡University of Tennessee, §Mississippi State University, ¶Oak Ridge National Laboratory

b.18. Identification of In-Beam Gamma Rays in ^{181}Hg (C. N. Davids, R. V. F. Janssens, H. Penttilä, B. Beck, D. J. Blumenthal, M. P. Carpenter, B. Crowell, R. G. Henry, T. Lauritsen, C. J. Lister, D. Nisius, D. T. Shi,† W. C. Ma,† B. Babu,† A. V. Ramayya,† K. Bindra,† J. H. Hamilton,† J. Kormicki,† L. T. Brown,† and U. Garg‡)

The interest in studying the neutron-deficient Hg isotopes stems from the fact that they are located in a region of the nuclear landscape where shape changes occur and where very large deformations were predicted. More specifically, the investigation of odd-A nuclei enables one to identify the orbitals located in the vicinity of the Fermi surface which play a crucial role in determining global properties such as nuclear shapes. Prior to this experiment, the ^{183}Hg nucleus studied by this collaboration[1] was the lightest odd-A Hg isotope known. From a recent experiment performed at the FMA in conjunction with 10 Compton-suppressed Ge detectors from the Argonne Notre Dame gamma-ray facility, it was possible to identify transitions in ^{181}Hg following the ^{144}Sm(^{40}Ar,3n) reaction at a beam energy of 175 MeV. A level scheme was constructed and the transitions were regrouped into three rotational bands. One of these is proposed to be built on the [521]$1/2^-$ groundstate and the two others are interpreted as signature partner bands built on the [624]$9/2^+$ configuration. The statistics in this experiments were not sufficient to obtain multipolarity information and an additional measurement was proposed.

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†Vanderbilt University, ‡University of Notre Dame.

[1]K. S. Bindra et al., Phys. Lett. B318, 41 (1993).

b.19. Spectroscopy of ^{189,187}Pb from Gamma-FMA Coincidences

(R. V. F. Janssens, C. N. Davids, D. Blumenthal, T. Brown, M. P. Carpenter, L. Conticchio, D. Gassmann, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Nisius, A. Baxter,¶ A. P. Byrne,¶ and G. D. Dracoulis¶)

The very neutron-deficient Pb isotopes are of much current interest because they exhibit shape coexistence between a spherical groundstate and a deformed prolate excited configuration located very low in excitation energy. Last year the nucleus ^{186}Pb was studied at the FMA in an FMA-γ-γ coincidence experiment.[1] The purpose of the present measurement was to delineate, for the first time, the groundstate and near groundstate excitations in the odd Pb isotopes ^{189,187}Pb in order to identify the orbitals which have an important role in driving the nuclear shape. The experiment was performed only very recently at the FMA with 10 Compton-suppressed Ge detectors from the Argonne Notre Dame BGO Gamma-Ray facility. ^{137}Pb was studied with the ^{155}Gd(^{36}Ar,4n) reaction at 179 MeV, while ^{189}Pb was reached with the ^{158}Gd(^{36}Ar,5n) reaction at the same beam energy. The analysis just began. It can already be stated that transitions in both Pb isotopes were identified and that it should be possible to establish level schemes. The presence of possible isomeric states in ^{189}Pb will be checked in a follow-up experiment planned in Canberra. A similar measurement on ^{187}Pb appears very difficult because of the very small cross section involved.

¶Australian National University, Canberra, Australia.

[1]A. M. Baxter et al., Phys. Rev. C 48, R2140 (1993).

b.20. Studies of ^{194,195,197}Po

(M. P. Carpenter, I. Ahmad, B. Crowell, C. Davids, R. V. F. Janssens, R. G. Henry, T. L. Khoo, T. Lauritsen, D. Nisius, H. Penttilä, W. Younes,† J. A. Cizewski,† L. A. Bernstein,† H. Q. Jin,† and D. P. McNabb†)

The energy systematics of low-lying polonium states show sudden changes near N = 114. The observed drops in the low-lying levels of ^{196,198}Po relative to the heavier isotopes indicate significant changes in the underlying structure of these nuclei. It is thought that this change is due to the onset of vibrational collectivity brought about by the quadrupole interaction between neutron and proton pairs. In order to extend the Po systematics even further, we measured, for the first time, states in ^{194,195,197}Po using the ^{28}Si + ^{170}Yb reaction at a beam energy of 142 MeV. The beam was supplied by ATLAS, and the data were taken with 10 Compton-suppressed Ge detectors placed at the target position of the Fragment Mass Analyzer.

Preliminary level schemes were constructed for ^{194,195,197}Po based on γ-γ and γ-FMA coincidences. The results for ^{194}Po show that the 2^+ - 0^+ transition energy decreased in energy by 140 keV relative to ^{196}Po suggesting that this nucleus moved beyond the vibrational limit to more collective motion. An extrapolation of the systematics predicts that the 2^+ energy could drop another 140 keV between ^{194}Po and ^{192}Po which would indicate the onset of rotational motion. Currently, we have an approved experiment to investigate the decay of yrast isomers in ^{194}Po which will allow us to (i) confirm our earlier level scheme of ^{194}Po, and (ii) assess the experimental conditions needed for a future study of ^{192}Po.

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†Rutgers University

b.21. Heavy Nuclei Far from Stability in the N < 126, Z > 82 Region (B. B. Back, D. J. Blumenthal, M. P. Carpenter, B. Crowell, C. N. Davids, D. J. Henderson, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Nisius,| H. T. Penttilä, I. G. Bearden, S. J. Freeman,† J. L. Durell,† M. J. Leddy,† A. G. Smith,† S. J. Warburton,† J. A. Becker,‡ P. Chowdhury,§ and E. F. Moore¶)

There are long-standing calculations suggesting that nuclei in the N < 126, Z > 82 region far from stability exhibit deformation effects. Away from stability an observable permanent quadrupole deformation should be achieved but, as yet, there is no experimental evidence for such an effect. A series of experiments was performed to assess the production of nuclei in this region and to study their structure. These experiments were performed using gamma-ray spectroscopy to investigate the low-lying level schemes and alpha-particle spectroscopy in order to isolate fine structure in the decay.

The low-lying level structure of the neutron-deficient isotope ^{202}Rn was studied, for the first time, using the ^{181}Ta(^{27}Al,6n) and ^{192}Pt(^{16}O,6n) reactions. Gamma-ray transitions between excited states in ^{202}Rn were identified by mass tagging the Fragment Mass Analyzer and by observation of coincident X rays. Transitions in ^{203}Rn were also identified. The level scheme deduced from these data is consistent with the systematics of light radon isotopes below the N = 126 shell closure and with theoretical calculations indicating that the ground-state shape should not be strongly deformed at N = 116.

Isotopes in the light actinide region with N < 126, Z > 82 were produced in the reaction of ^{28}Si on ^{182}W at beam energies of 164 and 170 MeV. Evaporation residues were selected using the FMA and implanted in a double-sided silicon strip detector. The charge-to-mass ratio of implanted ions, and energies and half lives of correlated α-decay events were used to make isotopic identifications. The α decay from the ground state of ^{204}Ra was observed, for the first time, with an α-particle energy of 7.488(12) MeV and a half life of 45^{+55}_{-21} ms. Previous results concerning the decay of ^{205}Ra were also confirmed. Statistics were too low to make a good test for the presence of fine structure in the decay. An experiment is planned to assess the production rates in this region using more symmetric reaction systems.

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†University of Manchester, United Kingdom, ‡Lawrence Livermore National Laboratory, §Wellesley College, ¶North Carolina State University.

C. EXOTIC NUCLEI, EXPERIMENTS WITH SECONDARY BEAMS AND EXOTIC BEAMS FACILITY INITIATIVE

With the Fragment Mass Analyzer (FMA) installed at ATLAS it is possible to explore the properties of nuclei at the very limit of stability. A research program was initiated at the FMA where the essential properties of new isotopes, such as masses, decay modes, and the associated half-lives are measured. During the past year, with the use of the implantation facility at the FMA focal plane, the heaviest proton emitters known thus far were discovered: ^{171}Au, ^{185}Bi and ^{167}Ir. Alpha decay studies concentrated on ^{181}Pb and on ^{192,194}Po and a beta decay study of the N = Z nucleus ^{68}Se was undertaken as well.

Experiments in the areas of astrophysics and applied physics utilizing some unique features of secondary (radioactive) beams began with the successful acceleration at ATLAS of the 1.8-hr ^{18}F isotope. A measurement of the ^{18}F(p,α) reaction involved in the transition from the hot CNO cycle to the rp-process was performed. A program of wear analysis with ^{18}F is being developed.

It is now widely recognized in the nuclear physics community that the acceleration of unstable beams opens up new research frontiers. To explore this new dimension, an extension of present technical capabilities and facilities is needed. Work towards the development of such a facility was undertaken in the Physics Division together with the community of scientists involved with ATLAS and others interested in this area of research. A working group is concentrating on the physics case for radioactive beams and on a novel technical concept for a facility with substantial capabilities incorporating ATLAS. An experiment exploring the production of neutron-rich isotopes with 100-MeV neutrons, 200-MeV deuterons and 200-MeV protons was performed in order to test some of the calculations that were done. A working document summarizing the current status of the discussions was prepared.

a. Study of Proton Radioactivities (C. N. Davids, B. B. Back, D. J. Henderson, C.-L. Jiang, H. T. Penttilä, A. H. Wuosmaa, P. J. Woods,* C. R. Bingham,† L. T. Brown,‡ B. Busse,§ L. Conticchio,¶ M. Freer,|| P. Joshi,** R. D. Page,* A. V. Ramayya,‡ J. D. Richards,† K. S. Toth,†† W. B. Walters,¶ and B. E. Zimmerman†)

About a dozen nuclei are currently known to accomplish their radioactive decay by emitting a proton. These nuclei are situated far from the valley of stability, and mark the very limits of existence for proton-rich nuclei: the proton drip line. A new 39-ms proton radioactivity was observed following the bombardment of a ^{96}Ru target by a beam of 420-MeV ^{78}Kr. Using the double-sided Si strip detector implantation system at the FMA, a proton group having an energy of 1.05 MeV was observed, correlated with the implantation of ions having mass 167 (see Figure I-31). The subsequent

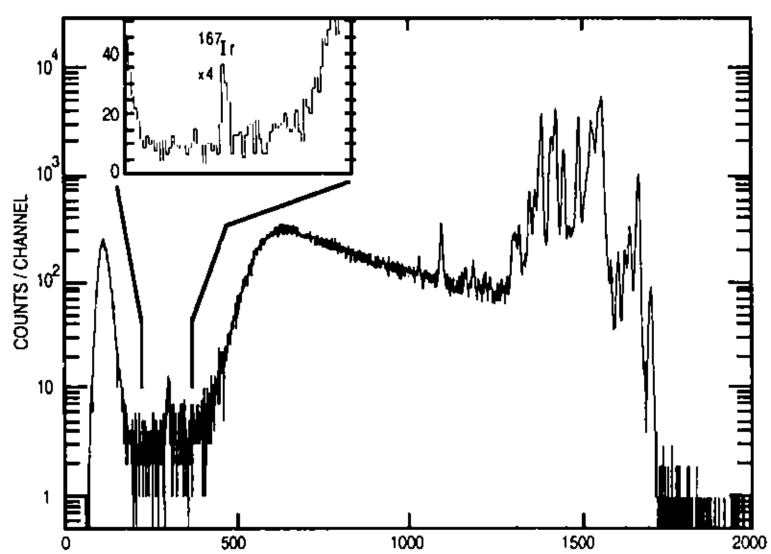

Fig. I-31. The energy spectrum of all decay events, with the ^{167}Ir proton group appearing at an energy just above 1 MeV.

*University of Edinburgh, UK, †University of Tennessee, ‡Vanderbilt University, §Oregon State University, ¶University of Maryland,||University of Birmingham, UK, **Louisiana State University, ††Oak Ridge National Laboratory.

daughter decay was identified as ^{166}Os by its characteristic alpha decay, and therefore the proton emitter is assigned to the ^{167}Ir nucleus. Further analysis showed that a second weak proton group from the same nucleus is present, indicating an isomeric state. Two other proton emitters were discovered recently at the FMA: ^{171}Au and ^{185}Bi, which is the heaviest known proton radioactivity. The measured decay energies and half-lives will enable the angular momentum of the emitted protons to be determined, thus providing spectroscopic information on nuclei that are beyond the proton drip line. In addition, the decay energy yields the mass of the nucleus, providing a sensitive test of mass models in this extremely proton-rich region of the chart of the nuclides. Additional searches for proton emitters will be conducted in the future, in order to extend our knowledge of the location of the proton drip line.

b. Alpha Decay of ^{181}Pb (C. N. Davids, D. J. Henderson, R. Hermann, H. Penttilä, A. Wuosmaa, K. S. Toth,* B. E. Zimmerman,† J. D. Richards,† C. R. Bingham,† W. B. Walters,‡ L. F. Conticchio,‡ and R. D. Page§)

The α-decay energy of ^{181}Pb was measured as 7211(10) keV[1] and 7044(15)[2]. In the first study the isotope was produced in ^{90}Zr bombardments of ^{94}Mo and, after traversing a velocity filter, implanted in a position-sensitive Si detector; no half life for ^{181}Pb was reported. In the second study the isotope was produced in ^{40}Ca bombardments of ^{144}Sm and transported to a position in front of a Si(Au) surface barrier detector with a fast He-gas-jet capillary system; an estimate of 50 ms was determined for the ^{181}Pb half life.

Recently we investigated ^{181}Pb α decay at ATLAS as part of a survey experiment in which a 1-pnA beam of 400-MeV ^{92}Mo was used to irradiate targets of ^{89}Y, ^{90,92,94}Zr, and ^{92}Mo to examine yields for one- and two-nucleon evaporation products from symmetric cold-fusion reactions. Recoiling nuclei of interest were passed through the Fragment Mass Analyzer and implanted in a double-sided silicon strip detector for α-particle assay. With the ^{90}Zr target we observed a group at 7065(20) keV which was correlated with A = 181 recoils and had a half life of 45(20) ms. Our new results for ^{181}Pb therefore agreed with those of the second study. There was no indication in the ^{90}Zr + ^{92}Mo data of the 7211(10)-keV α particles seen by Keller et al. The interested reader is referred to the 1993 atomic mass evaluation wherein the input α-decay energies and resultant masses of the light Pb isotopes (including ^{181}Pb) are discussed.

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*Oak Ridge National Laboratory, †University of Tennessee, ‡University of Maryland, §University of Edinburgh, United Kingdom.

[1]J. G. Keller et al., Nucl. Phys. A452, 173 (1986), [2]K. S. Toth et al., Phys. Rev. C 39, 1150 (1989)

c. Search for Shape Coexistence in ^{188,190}Pb via Fine Structure in the Alpha Decay of ^{192,194}Po (I. Ahmad, C. Davids, R. V. F. Janssens, H. Penttilä, B. E. Zimmerman,* C. R. Bingham,* J. D. Richards,* M. Huyse,† N. Bijnens,† J. Wauters,† P. van Duppen,† W. B. Walters,‡ L. F. Conticchio,‡ and K. S. Toth§)

The interaction between coexisting shapes in nuclei near closed shells was of great interest in the past decade. Excited 0^+ states at low energy can often be identified as the bandheads of structures with differing shapes built on those states. These structures were identified in $^{190-198}$Pb via beta decay and alpha decay "fine structure" studies.

Coexistence of different shapes in Pb nuclei was predicted by Nilsson-Strutinsky calculations, in which both the oblate and prolate minima were predicted to have excitation energies near 1 MeV. It was our intention to continue the systematic study of the Pb nuclides by searching for excited 0^+ states in ^{188}Pb by observing the fine structure in the alpha decay of ^{192}Po.

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*University of Tennessee, †IKS, Katholieke University, Leuven, Belgium, ‡University of Maryland, §Oak Ridge National Laboratory.

Ions of ^{192}Po were produced via the reaction of 192-MeV ^{40}Ca on a 500-μg/cm^2 ^{156}Gd target. A parallel-plate avalanche counter (PPAC) was positioned in the focal plane of the FMA to permit mass identification of the reaction recoils. The recoils were implanted into a double-sided silicon strip detector (DSSD) which allows correlations to be made between recoil events and their subsequent decays by using 48 strips in both the x- and y-directions to create 2304 effective pixels over the face of the detector. A thick (700-μm) Si(Li) detector was also positioned behind the DSSD to search for E0 conversion electrons which could be evidence of transitions between the various excited 0^+ states and between these states and the ground state. For each event, mass, time, energy, and position (in the DSSD) information was recorded.

The low yields of ^{192}Po obtained in the experiment were subsequently found to be due to a problem with the ^{40}Ca beam, and the experiment will be repeated using the ^{36}Ar + ^{160}Dy reaction.

d. Mass and Beta Decay of the N = Z Isotope ^{68}Se (D. J. Blumenthal, C. N. Davids, C. J. Lister, H. T. Penttilä, J. Batchelder,* D. S. Brenner,† L. T. Brown‡, B. Busse§, L. Conticchio,¶ D. Mustillo,¶ A. V. Ramayya,‡ J. Swider,¶ and W. B. Walters¶)

An experiment to measure the mass and beta decay of the N = Z nuclide ^{68}Se was performed. The properties of ^{68}Se are important for determining the abundance of proton-rich nuclei such as ^{60}Ni and ^{64}Zn, which are thought to be formed in the alpha-rich freezeout stage of a giant star. The abundances of the even-even N = Z nuclei such as ^{60}Zn, ^{64}Ge, and ^{68}Se depend on the competition between (α,γ) and (γ,α) reactions, whose rates depend sensitively on the reaction Q-values. In addition, the half-life of ^{68}Se is important in determining the path of the explosive rp-process, since reactions such as (p,γ) must compete with beta decay in order to push the rp path to heavier nuclei. Using the moving tape collector system and the $^{12}C(^{58}Ni,2n)^{68}Se$ reaction at 200 MeV, recoils were mass-selected by a slit at the FMA focal plane and implanted into the tape. After a 50-second collection period, the accumulated activity was moved to the counting position between two Ge gamma-ray detectors or a plastic scintillator beta detector and a Ge detector. The half-life of ^{68}Se was determined to be 37 ± 5 s, in agreement with other measurements.[1] Gamma-gamma and beta-gamma coincidence data are under analysis, to produce the decay scheme and the electron capture decay energy.

*Louisiana State University, †Clark University, ‡Vanderbilt University, §Oregon State University , ¶University of Maryland.

[1]P. Bairmann et al., Phys. Rev. C 50, 1180 (1994).

e. Using the FMA for Radiative Capture Cross-Section Measurements of Interest to Astrophysics (C. N. Davids, B. B. Back, D. J. Blumenthal, D. J. Henderson, R. Hermann, H. T. Penttilä, L. T. Brown,* B. Busse,† M. Gai,‡ A. Garcia,§ J. Görres,§ J. E. McDonald,‡ S. Vouzoukas,§ E. L. Wilds,‡ and P. J. Woods¶)

We assessed the capability of the Fragment Mass Analyzer (FMA) to study radiative capture reactions of astrophysical interest using inverse kinematics. Results from measurements on the $^1H(^{13}C,^{14}N)\gamma$ reaction show that the FMA is an ideal high-efficiency tool for these experiments, where the recoil ion is detected and identified at the FMA focal plane. Intermediate slits acting on energy/charge and mass/charge were introduced into the FMA, which reduced the scattered primary beam fraction at the focal plane to $<10^{-11}$. A small gas ionization chamber was placed behind the position-sensitive focal- plane detector, followed by a Si detector. Measurements of mass/charge, energy loss, and residual energy of the transmitted ions were made, giving at least

*Vanderbilt University. †Oregon State University, ‡University of Connecticut, §University of Notre Dame, ¶University of Edinburgh.

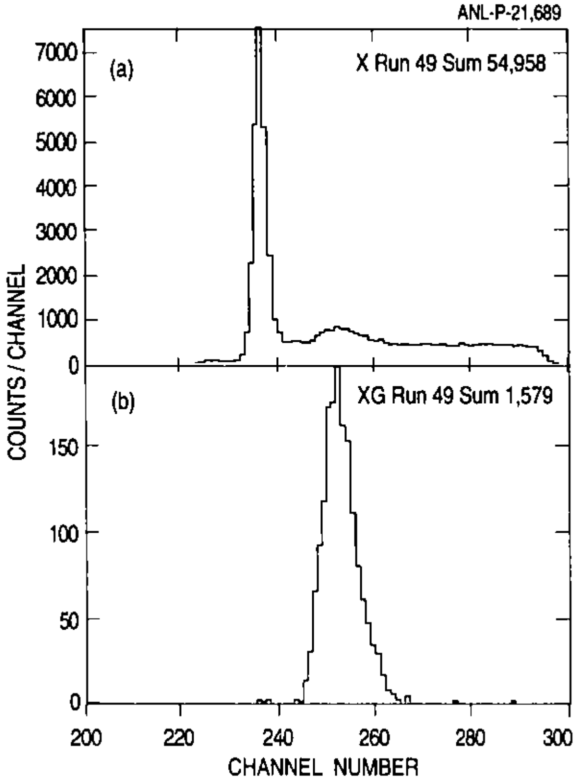

Fig. I-32. The position spectrum at the FMA focal plane. Panel (a) is the raw spectrum, panel (b) is gated by ^{14}N events identified by the gas ionization chamber.

another two orders of magnitude separation of recoils from scattered beam (see Figure I-32). A new ionization detector operating in the same gas volume as the focal plane detector will provide even better separation by eliminating the need for two of the three windows used in the test measurement.

At energies of ~ 0.5 MeV/nucleon, the recoil ions populate primarily a single charge state, resulting in a detection efficiency of > 50%. This will be particularly valuable for use with radioactive beams.

f. Measurement of the Astrophysical S-Factor for the $^{18}F(p,\alpha)$ Reaction at E = 662 keV/u with a ^{18}F Radioactive Beam (K. E. Rehm, D. J. Blumenthal, J. Gehring, D. Henderson, C.-L. Jiang, J. Nolen, R. C. Pardo, J. P. Schiffer, M. Paul,* A. Roberts,† J. Nickles,† and R. E. Segel‡)

^{18}F is produced in stars during the so-called breakout from the hot CNO cycle and is important as one of the links connecting the HCNO cycle with the rp-process by producing ^{19}Ne via the $^{18}F(p,\gamma)$ reaction. There is, however, a competing reaction $^{18}F(p,\alpha)^{15}O$ which leads back into the CNO cycle. The importance of ^{18}F for producing ^{19}Ne therefore depends strongly on the (p,γ) to (p,α) cross sections ratio. We have begun to study the $^{18}F(p,\alpha)^{15}O$ reaction using a ^{18}F beam. ^{18}F, which is a well-studied PET isotope, is generated at the medical cyclotron of the University of Wisconsin.

Aqueous [^{18}F] fluoride ions are produced via the $^{18}O(p,n)^{18}F$ reaction using a 30-µA, 11.4-MeV proton beam bombarding a 95% enriched [^{18}O] water target and electroplated onto the end of a 3-mm diameter Al anode. After electroplating, the anodized Al is pressed into a copper cathode insert for the National Electrostatics Corporation SNICS ion source, transported to Argonne National Laboratory and installed in the ion source of the Tandem accelerator at ATLAS. With an activity at the end of the electroplating process of 530 mCi, the starting activity after 2 h, which is the time needed to transport and install the material in the SNICS source, was 250 mCi, corresponding to a total number of ^{18}F atoms of 8.8×10^{13}.

The $^{18}F^-$ ions extracted from the ion source were accelerated to 13.4 MeV (744 keV/u) in the tandem accelerator using the 4^+ charge state. This energy was chosen since recent measurements

*Hebrew University, Jerusalem, Israel, †University of Wisconsin, Madison, ‡Northwestern University.

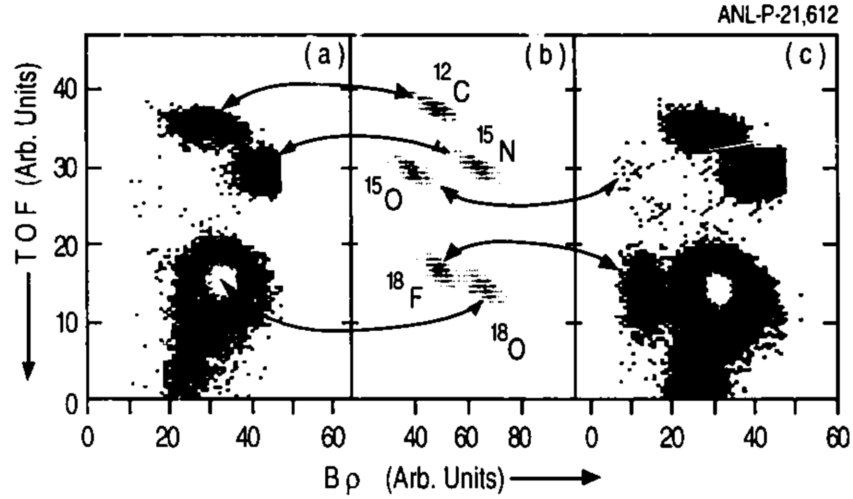

Fig. I-33. (a) Two-dimensional plot of time-of-flight (TOF) vs. magnetic rigidity (Bρ) measured with the gas-filled magnet for 13.4-MeV ^{18}O ions bombarding a polypropylene target. (b) Raytrace calculation for various ions in a gas-filled magnet. See text for details. (c) Same as (a) but with a mixed ^{18}F - ^{18}O sample in the ion source.

of the $^{19}F(^{3}He,t)^{19}Ne$ reaction found a broad state in ^{19}Ne at an excitation energy of about 7.07 MeV. For mass and Z identification the method of a gas-filled magnet was used. A spectrum of time-of-flight (TOF) vs. magnetic rigidity (Bρ) measured with the split-pole spectrograph is shown in Figure I-33 (a). The three groups of particles seen are attributed to elastically scattered ^{18}O ions, ^{15}N ions from the $^{18}O(p,\alpha)$ reaction and ^{12}C recoil ions. This identification was verified in a series of test measurements by generating recoil particles with the appropriate targets. In the same way the locations of ^{19}F, ^{16}O, ^{14}N and ^{13}C ions in the TOF vs Bρ plane were determined. The assignment of the various particle groups was verified by RAYTRACE calculations which in a Monte Carlo treatment take charge-changing collisions, energy-loss and straggling effects into account. A spectrum calculated for the split-pole spectrograph for ^{12}C, ^{15}N, ^{15}O, ^{18}O, and ^{18}F ions is shown in Fig. I-33 (b). This calculation reproduces qualitatively the relative location of ^{12}C, ^{18}O, and ^{15}N ions and, furthermore, predicts the location of the ^{18}F and ^{15}O groups which cannot be generated as recoil ions from elastic scattering. Figure I-33 (c) shows the spectrum obtained by scattering ^{18}O and ^{18}F ions from a polypropylene target when the 250 mCi ^{18}F sample was installed in the ion source. A comparison of Fig. I-33 (a) and I-33 (c) clearly shows excess counts in the area where ^{18}F and ^{15}O ions are expected. A cross section of 22 ± 7 mb/sr was extracted from the data corresponding to a resonance strength $\omega\gamma = 3.6 \pm 1.2$ keV. This value is not consistent with a $7/2^+$ or $1/2^-$ spin assignment for this state, but rather supports a $3/2^+$ state at this excitation energy. Improvements in the efficiency at the source and the transmission through the tandem accelerator by a factor of 10 are possible, which will allow an extension of these (p,α) experiments towards lower energies and a measurement of the $^{18}F(p,\gamma)$ reaction at similar energies.

g. Production and Test of ^{18}F Samples in the SNICS Ion Source (K. E. Rehm, M. Paul,* A. Roberts,† and J. Nickles†)

For experiments with ^{18}F beams the output of the SNICS ion source for fluorine ions was investigated. ^{18}F, which is a well-studied PET isotope, is generated at the medical cyclotron of the University of Wisconsin. Aqueous [^{18}F] fluoride ions are produced via the $^{18}O(p,n)^{18}F$ reaction using a 30-μA, 11.4-MeV proton beam bombarding a 95% enriched [^{18}O] water target. In order to minimize the ^{18}O component of the ^{18}F material the [^{18}F] fluoride must be separated from the [^{18}O] water. For this purpose the aqueous [^{18}F] fluoride solution (~ 0.5-1 ml) is removed from the production target and placed in a glassy carbon vessel. The vessel is heated to 115°C with He bubbling through the solution, evaporating the water while the ^{18}F adheres to the vessel walls. When dry, the vessel is filled with 1 ml ^{18}O-depleted 99.98% [^{16}O] water which is again evaporated. After this step is repeated once more the vessel is filled with 1.5 ml [^{16}O] water and 200-300 mole of natural KF as carrier material.

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Various techniques were tried to deposit the active ^{18}F-ions onto the SNICS cathode inserts. The method which produced the most stable compound used electrodeposition onto the end of a 3-mm diameter Al-rod. This material, however, requires conditioning of the ion source for up to 1 hour. Initial ^{18}F beam currents of 2 ppA were obtained. We are planning to test different deposition methods in order to produce samples which do not require any source conditioning.

h. Test of the Tandem Transmission at Low Terminal Voltages (K. E. Rehm, D. Blumenthal, J. Gehring, C.-L. Jiang, J. Nolen, R. C. Pardo, J. P. Schiffer, and M. Paul*)

For a planned experiment with ^{18}F beams at energies below 1 MeV/u the transmission of the Tandem-Linac system was investigated. The energies required in the experiment are typically around 600 keV/u, which for the most abundant charge states for F (4+) corresponds to terminal voltages between 2-3 MV. We studied the transmission from the source to the tandem accelerator and to the spectrograph in area II with ^{18}O and ^{19}F beams using two different approaches. In the first method only the tandem accelerator was used producing a 14-MeV DC ^{18}O beam. In the second method a pulsed beam was accelerated to 33 MeV with the tandem accelerator followed by deceleration to 14 MeV with the first 9 resonators of ATLAS. The total transmission from ion source to target was in both cases about 10%. Because of the smaller complexity we used the first method for the ^{18}F experiment. In future runs we are planning to use the electrostatic lens in the terminal of the tandem to improve the overall transmission.

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i. Study of Wear Analysis with ^{18}F (N. Schmidt, J. A. Nolen, D. J. Blumenthal, B. G. Glagola, J. P. Greene, C.-L. Jiang, M. Portillo, and K. E. Rehm)

We are studying the possible use of low-energy radioactive beams for the wear analysis of various industrial components (e.g. engine parts and materials for orthopedic implants). Previous experiments with ^{7}Be and ^{22}Na studied components at implantation depths of several tens of micrometer. In a first series of experiments we implanted ^{18}F ions into the surface layer, which opens the possibility to study wear in the critical first micrometer of various materials. ^{18}F was produced via the p(^{18}O,^{18}F)n reaction at $E_{^{18}O}$ = 110 MeV using a 1.22-mg/cm^2 polypropylene foil as a hydrogen target. The $^{18}F^{9+}$ ions were separated at $\theta = 0°$ from the incident $^{18}O^{8+}$ beam with the split-pole spectrograph. In order to allow for a rapid change of irradiation samples, the ^{18}F ions penetrated a thin HAVAR foil and were implanted into the sample which was located outside the vacuum chamber behind the pressure window. The depth distribution of the ^{18}F was tested by implantation into a series of 1.5-μ thick Mylar foils which were subsequently measured with respect to their ^{18}F activity using a Si-surface barrier detector. The localization of the ^{18}F ions was found to be better than 1.5 μ. The implantation depth could be varied in the range between 1.5 μ - 9 μ by choosing the appropriate distance between pressure window and implantation sample. The wear rate was determined by measuring the (decay-corrected) decrease of the activity remaining in the sample after it was polished with Emery paper. In a first experiment the wear of stainless steel could be measured by this technique with a sensitivity of better than 100 nm. A paper describing these results is under preparation.

j. Concept for an Advanced Exotic Beam Facility Based on ATLAS (K. E. Rehm, I. Ahmad, B. B. Back, C. N. Davids, W. F. Henning, R. V. F. Janssens, C.-L. Jiang, C. J. Lister, J. A. Nolen, J. P. Schiffer, and K. W. Shepard)

The acceleration of beams of unstable nuclei has opened up new research frontiers. Experiments at existing accelerators, and particularly at the first generation of radioactive ion beam facilities, have demonstrated convincingly that unique information becomes accessible. Critical cross sections for astrophysical processes that were impossible to obtain previously, qualitatively new and unexpected nuclear structure effects in nuclei far from stability, completely new approaches to

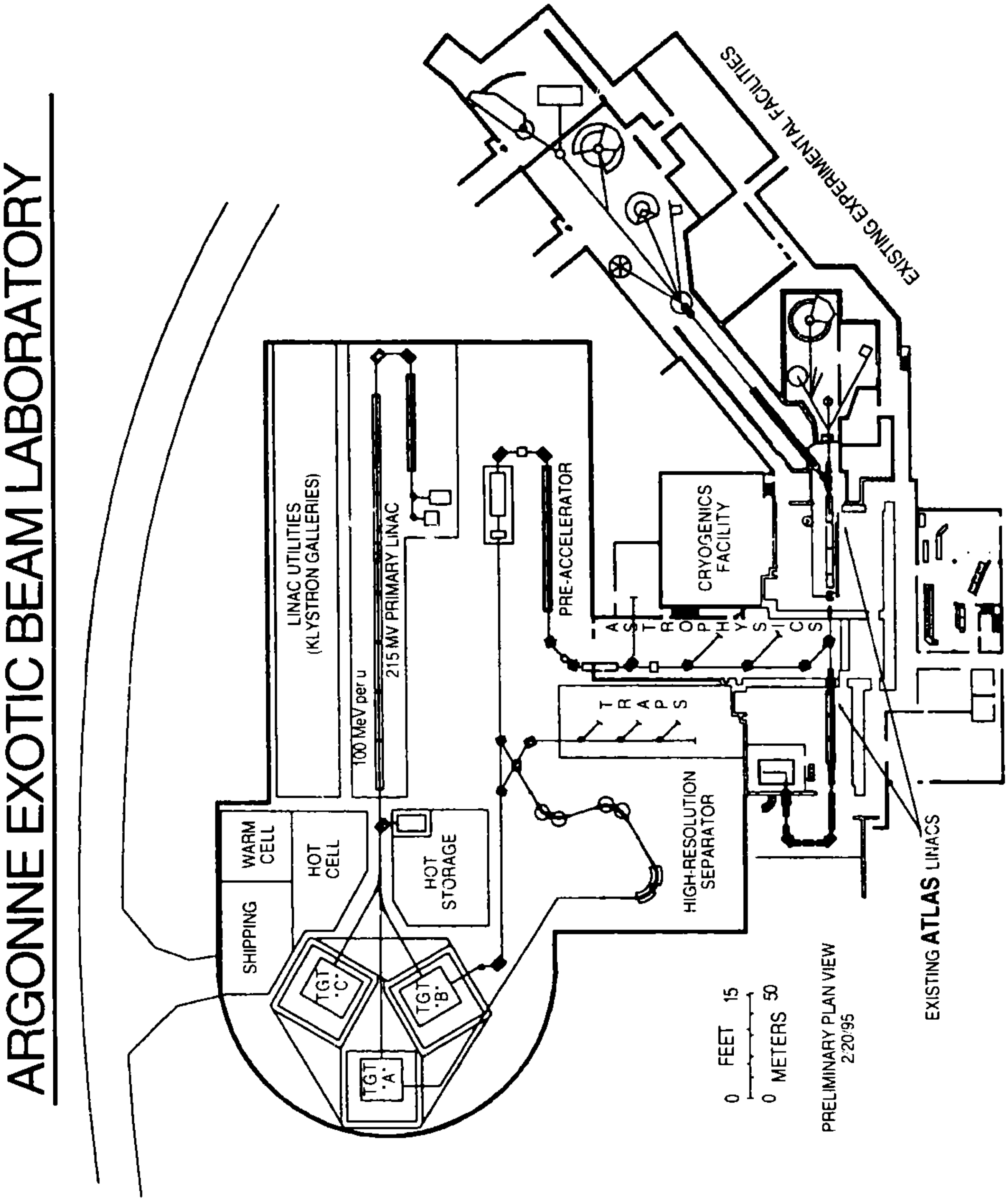

Fig. I-34. A preliminary layout of the Argonne Exotic Beam Facility showing the existing ATLAS building, accelerators, and experimental instrumentation, and the proposed new buildings, accelerators, target and handling cells, and experimental areas.

studies of nuclear decays, reactions and structure, all have triggered much excitement for this new dimension in nuclear research.

To explore this new dimension, an extension of present technical capabilities and facilities is needed. This need and its scientific basis were discussed in various workshops and symposia and in the Isospin Laboratory (ISL) White Paper. A report by the European community was published recently on prospects of radioactive beam facilities in Europe, and some next-generation projects for such facilities are starting in both Europe and Japan.

We prepared a document which summarizes the current status of discussions within the community of scientists involved with ATLAS, and others interested in this area of research, on the physics case for radioactive beams and on a novel technical concept for a facility with substantial capabilities incorporating ATLAS. The concept aims at achieving the physics goals set forth in the ISL White Paper, i.e. broad capabilities for research with radioactive beams, but is considerably more cost-effective than the concept laid out in the ISL document.

We propose a two-accelerator ISOL-type facility to provide intense beams of highest quality at the lower energies required for nuclear structure research and for reactions of astrophysical interest. As was extensively discussed, such an ISOL-type facility is truly complementary in its capabilities and research goals to those based on direct production of high energy secondary beams by projectile fragmentation.

Our base design shown in Figure I-34 uses a flexible approach for the primary accelerator and builds on the availability of the state-of-the-art heavy-ion accelerator ATLAS as the post accelerator. This is particularly important in view of the stringent beam quality requirements for nuclear structure and astrophysics experiments. The approach also allows timely construction of such a major facility.

The core idea of our concept shown in Figure I-34 is the use of about 0.1 pmA of 100-MeV neutrons from the breakup of 200-MeV deuterons. Spatial separation between the breakup target and the radioisotope production target solves some of the ion source problems encountered at high beam powers with charged-particle beams that undergo predominantly electronic (heat and radiation damage generating) energy loss. The purely nuclear energy loss and the long range of neutrons allow rather large target thicknesses to be used for more effective isotope production. To retain flexibility for optimizing secondary production yields by using a variety of radionuclide production mechanisms, our choice for the primary accelerator is a 215-MV linear accelerator which can deliver a range of ions at a beam power of 100 kW (beam currents of 1 mA for protons, 0.5 mA for deuterons, 0.25 pmA for alphas, 0.08 pmA for ^{12}C, and 0.06 pmA of ^{18}O).

Ion source configurations are based on the concepts and extensive experience gained at ISOL-type facilities (in particular at ISOLDE at CERN). In addition, the facility includes a high-resolution isobaric-mass separator, followed by a new low-q/m, low-velocity accelerator section, 90% of which is directly based on existing ATLAS superconducting technology. The beams are then either used directly after the ion source (for research with ion traps), after low-energy acceleration up to ~ 1 MeV/u (for experiments in nuclear astrophysics), or injected into the existing ATLAS facility for acceleration to energies above the Coulomb barrier (for studying nuclear reactions and structure).

ATLAS constitutes a state-of-the-art post accelerator well matched to this application. The recently completed uranium upgrade makes ATLAS unique worldwide in its capabilities of providing intense, high-quality, continuous-wave (100% duty cycle), heavy-ion beams for all elements up to and including uranium. ATLAS has excellent transverse and longitudinal phase space properties and excels in beam transmission and timing characteristics. Furthermore, the experimental equipment, including recently completed novel instrumentation such as the Fragment Mass Analyzer (FMA), are well matched to nuclear structure research.

The initial estimates of effort, timelines, and cost suggest that the facility discussed here could be built in a three-year construction period, following a two-year detailed facility design, at a cost of $109M in FY 1995 dollars. From our calculations of production yields and from beam extraction efficiencies which are based on experience at existing ISOL laboratories, such a facility would cover the physics goals set forth in the ISL White Paper. It will exceed the intensities specified in the White Paper for the largely unexplored region of neutron-rich nuclei, while providing approximately the intensities envisioned for proton-rich species. The cost is several times less than that of the concept tentatively adopted in the White Paper and represents a cost-effective and versatile scheme to address this exciting new domain of nuclear physics research.

k. Measurements of Yields of Fission Products in the Reaction of ^{238}U with High-Energy p, d and n Beams (J. A. Nolen, I. Ahmad, B. B. Back, K. Beyer, C. N. Davids, J. P. Schiffer, and R. Ronningen†)

An experiment was performed at the Michigan State University cyclotron to determine the yields of neutron-rich fission products in the reaction of ^{238}U with 100-MeV neutrons, 200-MeV deuterons and 200-MeV protons. Several 1-mm-thick ^{238}U foils were irradiated for 100-second intervals sequentially for each configuration and the ten spectra were added for higher statistics. The three successive spectra, each for a 40 s period, were accumulated for each sample. Ten foils were irradiated. Successive spectra allowed us to determine approximate half-lives of the gamma peaks. Several arrangements, which were similar to the setup we plan to use in our radioactive beam proposal, were used for the production of fission products. For the high-energy neutron irradiation, U foils were placed after a 5-inch-long, 1-inch-diameter Be cylinder which stopped the 200-MeV deuteron beam generating 100-MeV neutrons. Arrangements for deuteron irradiation included direct irradiation of U foils, placing U foils after different lengths of (0.5 inch, 1.0 inch and 1.5 inch) 2-inch diameter U cylinder. Since the deuteron range in uranium is 17 mm, some of the irradiations were due to the secondary neutrons from the deuteron-induced fission of U. Similar arrangements were also used for the 200-MeV proton irradiation of the ^{238}U foils. In all cases, several neutron-rich fission products were identified and their yields determined (see Figure I-35). In particular, we were able to observe ^{132}Sn in all the runs and determine its yield. The data show that with our proposed radioactive device we will be able to produce more than 10^{12} ^{132}Sn atoms per second in the target. Assuming an overall efficiency of 1%, we will be able to deliver one particle nanoampere of ^{132}Sn beam at a target location. Detailed analysis of the γ-ray spectra is in progress.

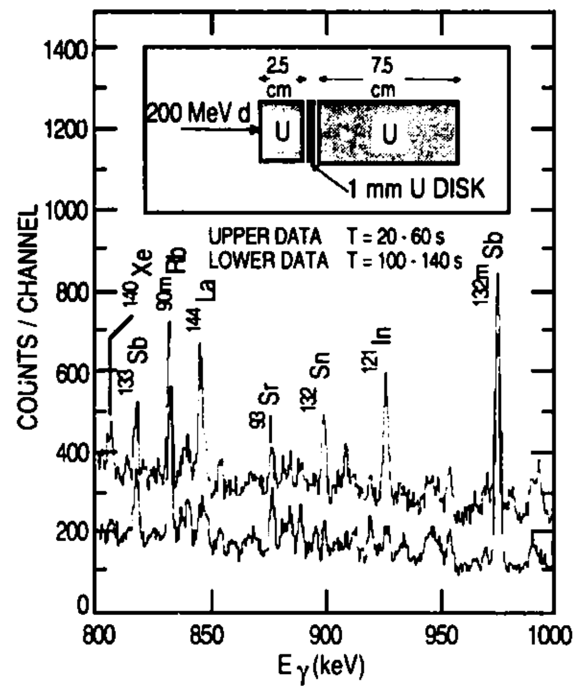

Fig. I-35. Portions of off-line γ-ray spectra of a thin ^{238}U disk irradiated with neutrons produced from a 200-MeV d beam stopping in a 2.5-cm-thick U piece. The spectra were measured with a 110% Ge detector and the time intervals were chosen to maximize the yields of ^{132}Sn, which has a 40 s half life.

ℓ. Production Rate Calculations for a Secondary Beam Facility (C.-L. Jiang, B. B. Back, and K. E. Rehm)

In order to select the most cost-effective method for the production of secondary ion beams, yield calculations for a variety of primary beams were performed ranging in mass from protons to ^{18}O with energies of 100-200 MeV/u. For comparison, production yields for 600-1000 MeV protons were also calculated. For light ion-(A < ^{4}He) induced reactions at energies above 50 MeV/u the LAHET code was used while the low energy calculations were performed with LPACE. Heavy-ion-induced production rates were calculated with the ISAPACE program. The results of these codes were checked against each other and wherever possible a comparison with experimental data was performed. These comparisons extended to very exotic reaction channels, such as the production of ^{100}Sn from ^{112}Sn and ^{124}Xe induced fragmentation reactions. These comparisons indicate that the codes are able to predict production rates to within one order of magnitude.

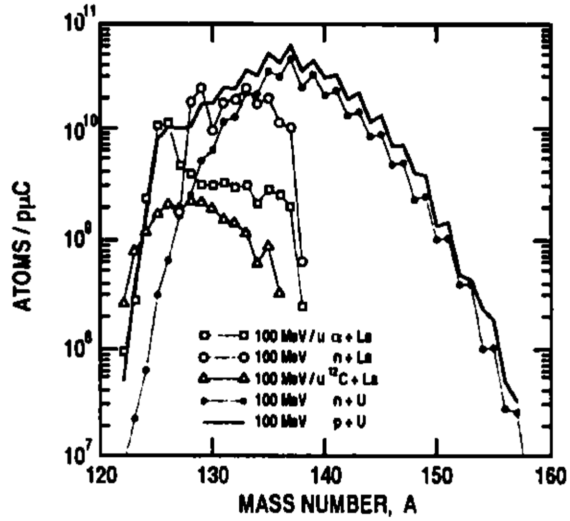

Fig. I-36. Comparison of the production rate of Cs isotopes using either 100-MeV/u beams from the presently proposed facility or 1000-MeV protons as proposed in the ISL White Paper. Calculations for light projectiles are performed with the LAHET code, whereas the IsaPace code was used for ^{12}C.

From the calculations it became clear that, in order to cover the full range of secondary particles ranging from neutron-deficient to neutron-rich secondary beams, different beam species from the driver accelerator are required. This is shown for the production of different Cs isotopes in Fig. I-36. Neutron-rich nuclei are best produced by n-induced fission of a U target. The highest production yields for neutron-deficient nuclei were obtained from 100-MeV/u ^{4}He or ^{12}C induced spallation reactions on targets which should be as close as possible in mass and charge to the required secondary beam particle. For the production of neutron-rich light nuclei (e.g. ^{11}Li) the best method was found to be fragmentation of 100-MeV/u ^{15}N and ^{18}O beams.

These calculations clearly demonstrated the need for a driver accelerator capable of accelerating a variety of primary beams ranging from protons to ^{12}C and ^{18}O.

Future calculations will include contributions from low-energy (< 20 MeV) neutrons to the production yields as well as the effects of finite release times from different targets.

m. Shielding Calculations for a Production Target for Secondary Beams (K. E. Rehm, B. B. Back, C.-L. Jiang, J. A. Nolen, and R. Ronningen*)

In order to estimate the amount of shielding required for a radioactive beam facility, dose rate calculations for production targets with different geometries were performed. The calculations were performed with the MSU shielding code assuming a 500-pμA 200-MeV deuteron beam stopped in a thick Al target. The target and the ion-optical elements for beam extraction are located in a 2 m^3 large volume at the center of the production cell. These dose rate calculations (see Figure I-37) show that with a combination of Fe and concrete it is possible to reduce the dose rate expected at the surface of a 7-m-wide cube housing the production target to less than 2 mrem/hr.

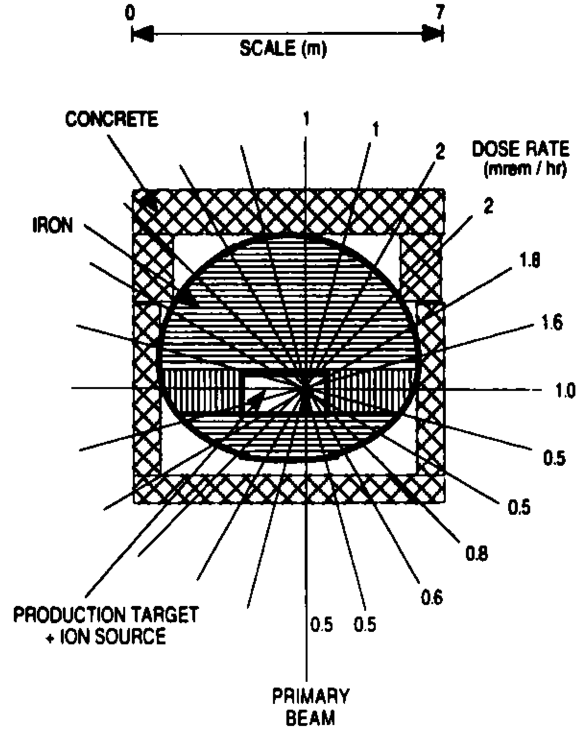

Fig. I-37. Schematic of a production target cell viewed from the top. The target, ion source, and the associated extraction optics is located in the 2m × 1m area which is surrounded by a combination of iron and concrete shielding. The beam is stopped in the target. The dose rate expected at the surface of the cell for a 200-MeV 500 μA deuteron beam stopped in an Al target at various angles is indicated.

n. Isobar Separator for Radioactive Nuclear Beams Project
(C. N. Davids and J. A. Nolen)

In order to produce pure beams of radioactive products emanating from the production target/ion source system, both mass and isobar separation is required. A preliminary mass separation with a resolution ΔM/M of approximately 10^{-3} will select the proper mass beam. An isobar separator is needed because the masses of adjacent isobars are usually quite close, especially for beams near stability. In general, a mass resolution of 5×10^{-5} is needed for isobar separation in the A < 120 region, while a resolution of 3×10^{-5} or better is needed for heavier masses.

Magnets are used to obtain mass separation. However, in addition to having mass dispersion properties, magnets also have an equal energy dispersion. This means that an energy variation in the beam cannot be distinguished from a mass difference. This is important because ions emerge from the ion source having a small (~ 10^{-5} - 10^{-4}) energy spread. In order to make the system respond only to mass differences, it must be made energy dispersionless. This is normally accomplished by using a combination of electric and magnetic fields. The most convenient way of doing this is to use an electric deflection following the magnet separator.

A preliminary isobar separator which achieves a mass resolution of 2.7×10^{-5} is shown in Figure I-38). It uses two large 60° bending magnets to obtain a mass dispersion of 140 mm/%, and four electric dipoles with bending angles of 39° to cancel the energy dispersion. Sextupole and octupole correction elements are used to reduce the geometrical aberrations.

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*Michigan State University.

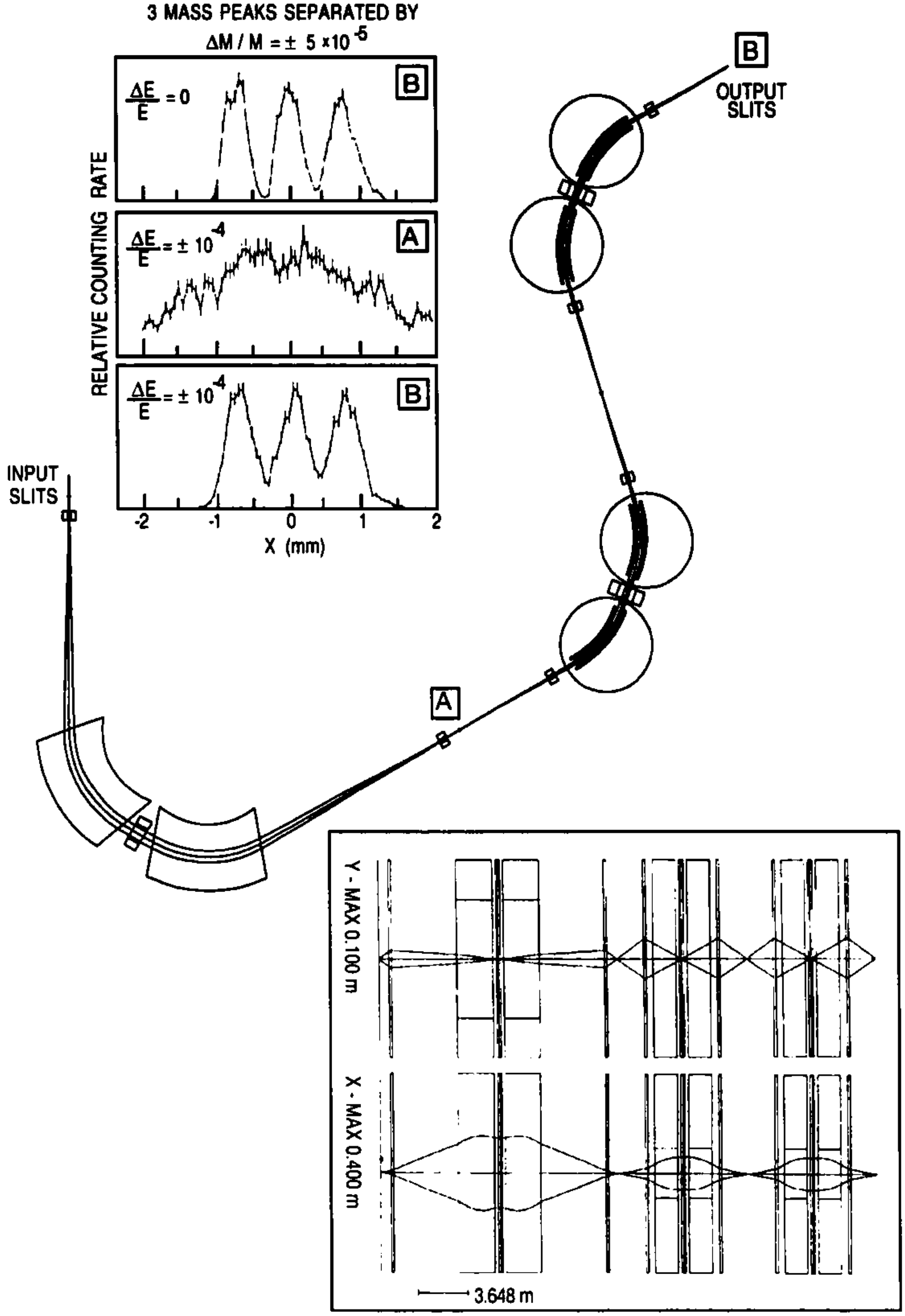

Fig. I-38. Schematic of the high-resolution mass separator. The location of the ion-optical elements (two magnetic and four electric dipoles) are indicated in the center part. Mass spectra for three masses with $\Delta M/M = \pm 5 \times 10^{-5}$ calculated under different assumptions about the incident energy uncertainty are shown at points A and B along the beam path. The beam profile expected along the mass sepa: ator is shown in the lower panel.

A major effort was mounted in the area of the physics associated with the strong fields produced in near-barrier collisions of very heavy ions such as U + Ta and U + Th. A new experiment (APEX), led by the Argonne group, was designed and constructed to study the phenomena hinted at by the results of experiments carried out over the past decade at GSI. Coupled with the completion of the ATLAS U-upgrade, APEX moved from the construction and testing phase to data production. Several highly successful runs were carried out, resulting in data sets for positron-electron pairs far greater than any of the published results. Many aspects of these data are still being analyzed. At this stage, however, the anomalous sharp sum-energy lines observed in previous experiments have not been seen.

In addition to the studies of strong fields and research programs outlined in previous sections, some effort devoted to other topics is also contained in this section. One of these efforts relates to the behavior of cooled beams of charged particles confined in storage rings and ion traps. This effort takes place both at the theoretical and experimental levels. In particular, measurements were performed at the ASTRID storage ring.

Our measurements of the half-life of ^{44}Ti are continuing with the goal of achieving a precision of ~5% for this isotope of importance in astrophysics. The impact of the ion charge state on the internal conversion process was studied in ^{83}Kr. This section also describes efforts within the PHOBOS Collaboration.

a. Studies of Positron Electron Pair Production in ^{238}U + ^{181}Ta (I. Ahmad, B. B. Back, R. R. Betts, R. W. Dunford, W. Kutschera, C. J. Lister, M. D. Rhein, J. P. Schiffer, P. Wilt, M. Wolanski, A. H. Wuosmaa, S. M. Austin,† F. P. Calaprice,‡ K. C. Chan,§ A. Chishti,§ P. Chowdhury,§ C. Conner,*** J. D. Fox,¶ S. J. Freedman,‖ M. Freer,** S. Gazes,†† J. S. Greenberg,§ A. L. Hallin,‡‡ T. Happ,§§ N. Kaloskamis,§ E. Kashy,† M. Liu,‡‡ M. R. Maier,‖ A. Perera,¶¶ E. Roa,¶ T. Trainor,‖‖ J. S. Winfield,† F. L. H. Wolfs,¶¶ G. Xu,§ A. Young,‡ and J. E. Yurkon†)

Following the completion of APEX in late 1993, a two-week run on the ^{238}U + ^{181}Ta system at 6.1 and 6.3 MeV/u with 1 mg/cm^2 targets provided, for the first time, data in which the expected

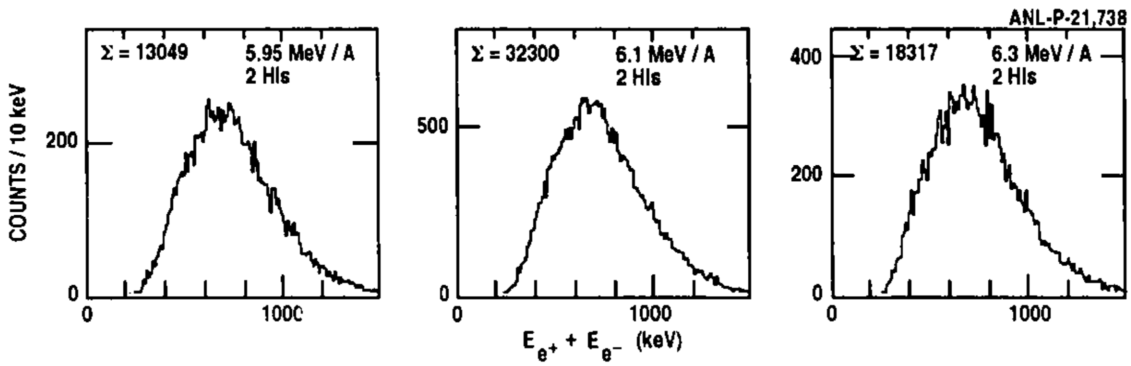

Fig. I-39. Sum-energy spectra of positrons and electrons produced in the ^{238}U + ^{181}Ta reaction at E_{lab} = 5.95, 6.1, and 6.3 MeV/u.

†Michigan State Univ., ‡Princeton Univ., §Yale Univ., ¶Florida State Univ., ‖Univ. of California, Berkleley, **Univ. of Birmingham, UK, ††Univ. of Chicago, ‡‡Queen's Univ., Ont., §§GSI, Darmstadt, Germany, ¶¶Univ. of Rochester, ‖‖Univ. of Washington, ***Univ. of Illinois at Chicago.

sharp sum-energy lines should appear. Data from previous experiments show evidence for sharp sum-energy lines at 625, 748 and 805 keV, observed at bombarding energies from 5.9 to 6.3 MeV/u. The 625- and 809-keV lines display the characteristics of equal-energy back-to-back emission whereas the 748-keV line shows a rather different behavior. In our measurements, average beam currents of 2-3 pnA from the ATLAS accelerator were used to bombard 1-mg/cm^2 rolled ^{181}Ta targets, the energy loss in which corresponds to the ranges of bombarding energies over which the sharp sum-energy lines were previously reported. A run at 5.95 MeV/u for ^{238}U + ^{181}Ta followed in May 1994. These data were analyzed extensively. Sum-energy spectra measured in coincidence with scattered ions in the range $20^\circ \leq \theta \leq 68^\circ$ are shown in Fig. I-39. No evidence is found for the sharp sum-energy lines reported previously and, depending on the scenario assumed for the production mechanism and kinematics of the pairs, upper limits on cross sections at the 90% confidence limit range from 10-100 times smaller than the values that can be deduced from the earlier reports. We are in the process of refining the data analysis and simulations of the apparatus in order to finalize these numbers for publication.

b. Studies of Positron Electron Pair Production in ^{238}U + ^{232}Th (I. Ahmad, B. B. Back, R. R. Betts, R. W. Dunford, W. Kutschera, C. J. Lister, M. D. Rhein, J. P. Schiffer, P. Wilt, M. Wolanski, A. H. Wuosmaa, S. M. Austin,† F. P. Calaprice,‡ K. C. Chan,§ A. Chishti,§ P. Chowdhury,§ C. Conner,*** J. D. Fox,¶ S. J. Freedman,‖ M. Freer,** S. Gazes,†† J. S. Greenberg,§ A. L. Hallin,‡‡ T. Happ,§§ N. Kaloskamis,§ E. Kashy,† M. Liu,‡‡ M. R. Maier,‖ A. Perera,¶¶ E. Roa,¶ T. Trainor,‖‖ J. S. Winfield,† F. L. H. Wolfs,¶¶ G. Xu,§ A. Young,‡ and J. E. Yurkon†)

Following the non-observation of sharp sum-energy lines in our earlier ^{238}U + ^{181}Ta measurements, it was decided to pursue measurements of the ^{238}U + ^{232}Th system which, in the previously published work, showed the most striking evidence for near-equal-energy back-to-back pairs leading to sharp sum-energy lines. Following the refurbishing of the APEX silicon arrays and extensive tests of the rotating target wheel assembly, a major positron run took place in November 1994. Rolled 1-mg/cm^2 ^{232}Th targets were bombarded with 5.95-MeV/u ^{238}U. The target rotation allowed up to 2 pnA of beam to be used without serious deterioration of the targets. Over 300,000 pairs were accumulated, representing an order-of-magnitude improvement in statistics over the previously published results. Preliminary analysis shows no evidence for the sharp lines at a cross section level orders of magnitude below those previously reported. The analysis of these data is currently being completed in preparation for publication.

c. Measurement of Internal Pairs from ^{206}Pb (I. Ahmad, B. B. Back, R. R. Betts, R. W. Dunford, W. Kutschera, C. J. Lister, M. D. Rhein, J. P. Schiffer, P. Wilt, M. Wolanski, A. H. Wuosmaa, S. M. Austin,† F. P. Calaprice,‡ K. C. Chan,§ A. Chishti,§ P. Chowdhury,§ C. Conner,*** J. D. Fox,¶ S. J. Freedman,‖ M. Freer,** S. Gazes,†† J. S. Greenberg,§ A. L. Hallin,‡‡ T. Happ,§§ N. Kaloskamis,§ E. Kashy,† M. Liu,‡‡ M. R. Maier,‖ A. Perera,¶¶ E. Roa,¶ T. Trainor,‖‖ J. S. Winfield,† F. L. H. Wolfs,¶¶ G. Xu,§ A. Young,‡ and J. E. Yurkon†)

The failure to observe sharp sum-energy lines in measurements of ^{238}U + ^{181}Ta and ^{238}U + ^{232}Th raises the issue of the correct functioning of APEX under in-beam conditions. Extensive measurements with electron and pair emitting sources were used to demonstrate the resolution and acceptance of APEX, but the possibility remains that some unforeseen background or other effects

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†Michigan State University, ‡Princeton University, §Yale University, ¶Florida State University, ‖University of California, Berkeley, **University of Birmingham, United Kingdom, ††The University of Chicago, ‡‡Queen's University, Kingston, Ontario §§GSI, Darmstadt, Germany, ¶¶University of Rochester, ‖‖University of Washington ***University of Illinois at Chicago.

might compromise the ability to see peaks in-beam. In order to test the functioning of APEX under the most stringent conditions, we also performed a measurement of internal pairs produced in the decay of the 2.648-MeV 3^- state in ^{206}Pb to the 2^+ state at 0.803 MeV. The 3^- state was excited in the ^{206}Pb + ^{206}Pb reaction at 5.9 MeV/u with a cross section of roughly 40 mb, resulting in an expected pair cross section of approximately 16 μb. It should be emphasized that this measurement represents a much stricter test of the functioning of the apparatus than the observation of sum-energy lines would represent, as the internal pair measurement requires a Doppler shift correction before the transition can be seen. These data were analyzed and clearly show the expected peak. A Doppler-corrected sum-energy spectrum is shown in Fig. I-40, showing the expected IPC line at 823 keV. At present we are evaluating the acceptance of APEX for events of this type but it is clear that the observed yield is close to expectations.

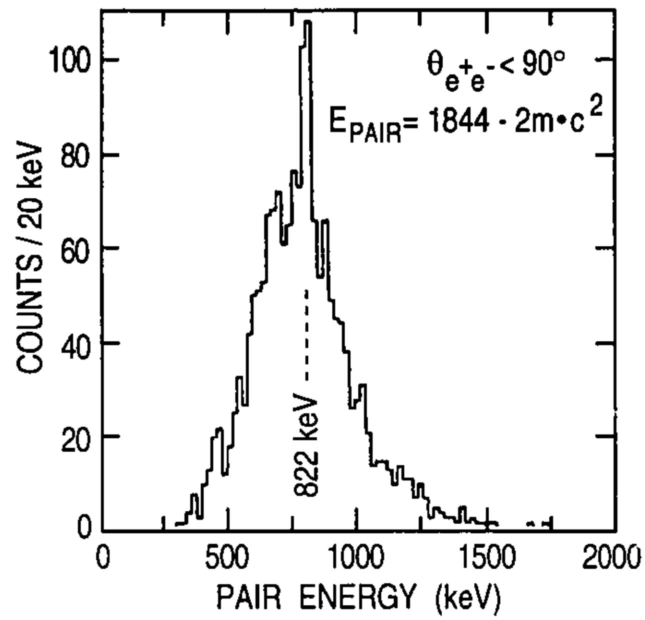

Fig. I-40. Doppler corrected sum-energy spectrum for ^{206}Pb + ^{206}Pb at 5.85 MeV/u (preliminary).

d. Spectroscopy of High-Lying States in Actinide Nuclei (I. Ahmad, B. B. Back, R. R. Betts, M. P. Carpenter, B. Crowell, R. W. Dunford, R. V. F. Janssens, T. L. Khoo, W. Kutschera, T. Lauritsen, C. J. Lister, M. D. Rhein, J. P. Schiffer, P. Wilt, M. Wolanski, A. H. Wuosmaa, A. Aprahamian,† S. M. Austin,‡ F. P. Calaprice,§ K. C. Chan,¶ A. Chishti,¶ P. Chowdhury,¶ C. Conner,‡‡‡ J. D. Fox,|| S. J. Freedman,** M. Freer,‡‡ U. Garg,† S. Gazes,§§ J. S. Greenberg,¶ A. L. Hallin,¶¶ T. Happ,|||| N. Kaloskamis,¶ E. Kashy,‡ M. Liu,¶¶ M. R. Maier,** E. F. Moore,†† A. Perera,*** E. Roa,|| T. Trainor,††† J. S. Winfield,‡ F. L. H. Wolfs,*** G. Xu,¶ A. Young,§ and J. E. Yurkon‡)

In the course of studying positron-electron production during the collisions of uranium beams and tantalum targets, a careful measurement of the emitted gamma radiation was made using large Ge detectors. Many new high energy gamma rays were found, associated both with U-like and Ta-like fragments. To determine the origin of these gamma rays, a dedicated set of improved gamma-ray studies were carried out.

The studies used four large (> 55%) Ge detectors mounted in the APEX chamber. States in ^{238}U and ^{232}Th were Coulomb excited using a ^{208}Pb beam of 5.8 MeV/u. Heavy ions were detected in the large-area APEX multiwire proportional counters. The extensive beam monitoring of the APEX setup allowed precise normalization and accurate cross-section determinations. The Doppler shifts from upstream and downstream detectors permitted a precise confirmation of the

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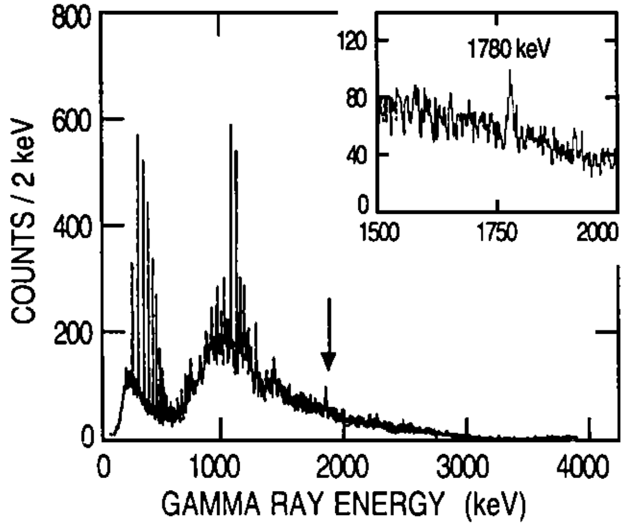

Fig. I-41. Doppler-corrected gamma-ray spectrum from $^{238}U + {}^{208}Pb$ at 5.8 MeV/u.

incident beam energy to less than 0.05 MeV/A. A spectrum of gamma rays, corrected assuming emission from ^{238}U is shown in Fig. I-41.

A strong transition was found in ^{238}U at 1780 keV. This is surprising, as most discrete transitions lie below 1200 keV and at higher energies an exponentially falling continuum of transitions is observed. The impact parameter dependence of the 1780-keV line precluded its origin arising from a transfer reaction. The width of the peak was larger than expected from Doppler reconstruction, indicating that it could be a composite of several transitions. No evidence was found to support the hypothesis that the state from which this γ ray originates is of two-phonon origin, as no decay branches to the known one-phonon vibrational states could be found. In ^{232}Th a rather different structure was observed, with many new weak transitions up to 1900 keV being found. Preliminary analysis indicates that the integrated strength of the lines in the 1750-1900-keV region in both ^{238}U and ^{232}Th are about 20 mb.

These observations may have relevance to the overall APEX positron puzzle, and certainly present an interesting new challenge to spectroscopy. The total cross section of production of high-lying strength now matches rather well with the cross-section previously reported for GSI positron-electron coincidences. There are, however, several features which make the observations difficult to reconcile, most notably the fact that the positron-electron yield from nuclear Internal Pair Conversion from swiftly moving ions should show large kinematic shifts and should not result in sharp peaks in the laboratory frame.

Detailed analysis is in progress in an attempt to understand the origin and structure of the states from which these γ rays emerge. Similar transitions observed recently in ^{238}U fluorescence experiments indicate the possibility of high-lying dipole strength, possibly associated with the collective M1 "scissors" mode.

e. Monte Carlo Studies of APEX (I. Ahmad, B. B. Back, R. R. Betts, R. W. Dunford, W. Kutschera, C. J. Lister, M. D. Rhein, J. P. Schiffer, P. Wilt, M. Wolanski, A. H. Wuosmaa, S. M. Austin,† F. P. Calaprice,‡ K. C. Chan,§ A. Chishti,§ P. Chowdhury,§ C. Conner,*** J. D. Fox,¶ S. J. Freedman,ll M. Freer,** S. Gazes,†† J. S. Greenberg,§ A. L. Hallin,‡‡ T. Happ,§§ N. Kaloskamis,§ E. Kashy,† M. Liu,‡‡ M. R. Maier,ll A. Perera,¶¶ E. Roa,¶ T. Trainor,llll J. S. Winfield,† F. L. H. Wolfs,¶¶ G. Xu,§ A. Young,‡ and J. E. Yurkon†)

An essential component in the assessment of the significance of the results from APEX is a demonstrated understanding of the acceptance and response of the apparatus. This requires detailed simulations which can be compared to the results of various source and in-beam

†Michigan State Univ., ‡Princeton Univ., §Yale Univ., ¶Florida State Univ., llUniv. of California, Berkeley, **Univ. of Birmingham, UK, ††The Univ. of Chicago, ‡‡Queen's Univ., Kingston, Ontario, §§GSI, Darmstadt, Germany, ¶¶Univ. of Rochester, llllUniv. of Washington, ***Univ. of Illinois at Chicago.

measurements. These simulations were carried out using the computer codes EGS and GEANT, both specifically designed for this purpose. As far as is possible, all details of the geometry of APEX were included. We compared the results of these simulations with measurements using electron conversion sources, positron sources and pair sources. The overall agreement is quite acceptable and some of the details are still being worked on. The simulation codes were also used to compare the results of measurements of in-beam positron and conversion electrons with expectations based on known physics or other methods. Again, satisfactory agreement is achieved. We are currently working on the simulation of various pair-producing scenarios such as the decay of a neutral object in the mass range 1.5-2.0 MeV and also the emission of internal pairs from nuclear transitions in the colliding ions. These results are essential input to the final results from APEX on cross section limits for various, previously proposed, sharp-line producing scenarios.

f. Nature of Ordering in Confined Crystalline Ionic Systems
(J. P. Schiffer)

Simulations continued studying the properties of systems of ions confined in ion traps or storage rings and cooled to very low temperatures, forming a strongly correlated non-neutral plasma. In particular the computer simulation of a large system of 20000 ions in isotropic confinement was continued to investigate whether a transition to the body-centered cubic order that is characteristic of infinite systems might occur. The simulations so far have not provided a conclusive answer. The systems show a characteristic shell structure, 18 spherical shells, very similar to what was seen in smaller simulations (see Figure I-42).

Simulations were also done with the same number of ions in anisotropic confinement. Here a surprising result is seen -- instead of forming a series of spheroidal shells, the anisotropy causes the outer shell to be spheroidal -- but the inner ones are formed at a fixed distance from the outermost shell -- giving shapes that are not spheroids and exhibit discontinuous edges (see Figure I-43). The relevance of these phenomena to ion traps needs to be investigated.

*Århus University, Denmark.

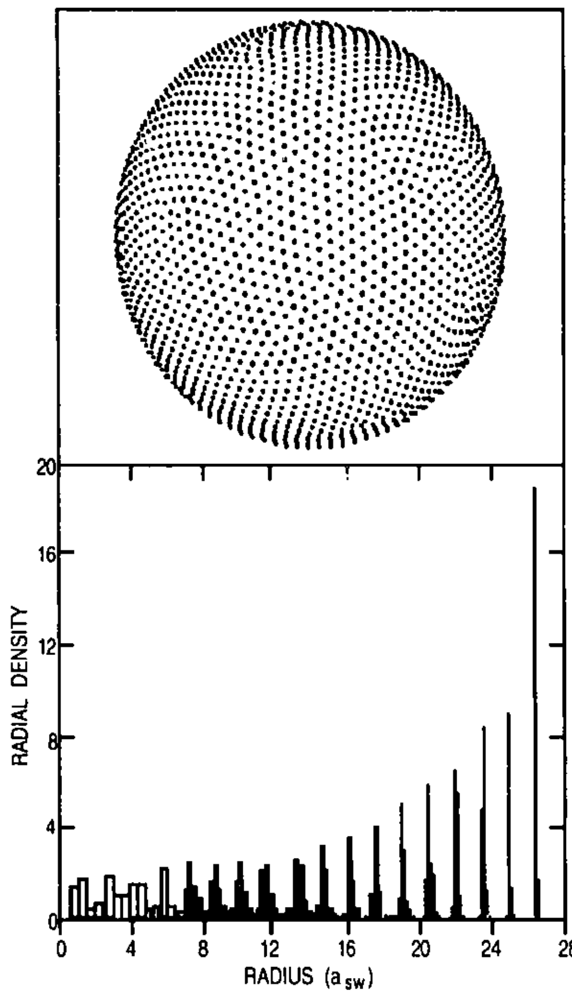

Fig. I-42. Simulation of 20,000 ions in an isotropic trap. On top, the outer shell of ions is shown, on the bottom the radial density. The distance scale is in units of the Seitz-Wigner radius ($4/3\ \pi a_{SW}^3 = 1/\rho$).

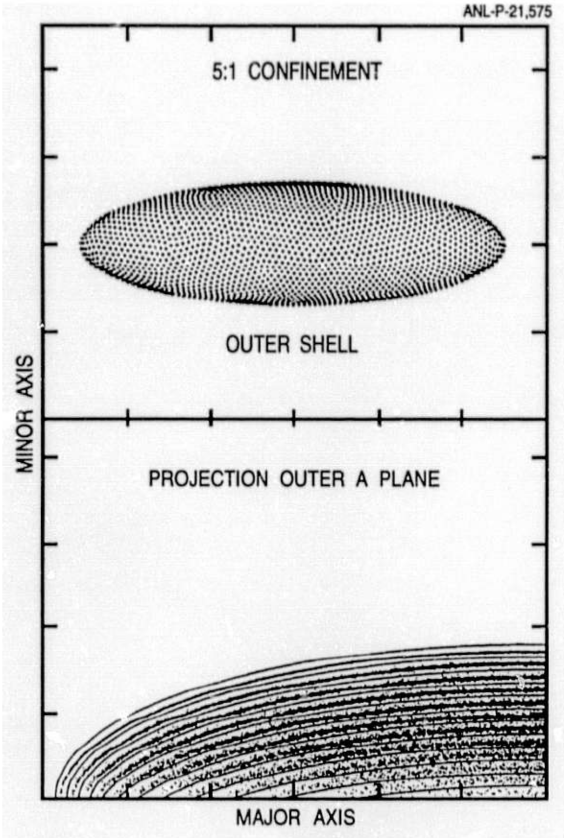

Fig. I-43. Simulation of 20,000 ions in anisotropic confinement with the restoring force in the z-direction 5 times less than in x and y. The ions in the outer spheroidal shell are shown on top, while on the bottom a projection of particles onto the z-ρ plane is plotted. The lines are drawn to emphasize the fact that in the interior the ions do not settle onto spheroidal surfaces, but on ones that are fixed perpendicular distance from the outer (spheroidal) shell.

g. Normal Modes of Confined Cold Ionic Systems (J. P. Schiffer and D. H. Dubin*)

The normal modes of a cloud of confined ions forming a strongly-correlated plasma were investigated. The results of molecular-dynamics simulations were compared to predictions of a cold fluid mode. Mode frequencies are observed to shift slightly compared to the cold fluid predictions, and the modes are also observed to damp in time. Simulations also reveal a set of torsional oscillations which have no counterpart in cold fluid theory. The frequency shift, damping, and torsional effects are compared to a model that treats trapped plasmas as a visco-elastic spheroid.

It may be possible to measure high-frequency bulk and shear moduli of a strongly-correlated plasma from mode excitation experiments on trapped nonneutral plasmas. An example of the results of the calculation is presented in Fig. I-44.

*University of California, San Diego.

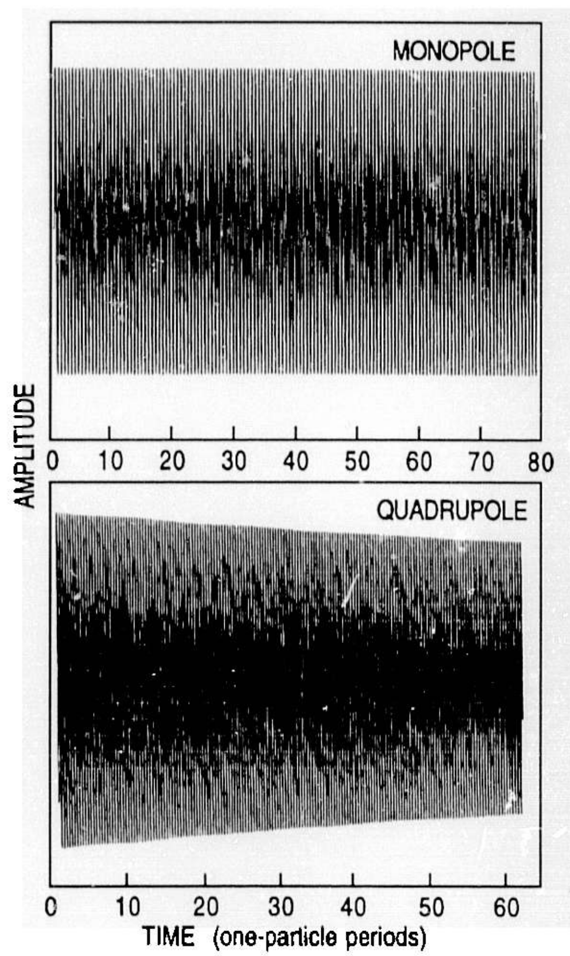

Fig. I-44. Oscillations of a cold ion cloud of 1000 ions in isotropic confinement, when subjected to a perturbation the monopole excites a pure radial mode (top) and when a quadrupole mode is excited. Time is in units of the period of one particle oscillating in the same confining field.

h. Laser-Cooled Continuous Ion Beams (J. P. Schiffer, J. S. Hangst,* J. S. Nielsen,* O. Poulsen,* and P. Shi*)

A collaboration with a group in Århus, Denmark, using their storage ring ASTRID, brought about better understanding of ion beams cooled to very low temperatures. The longitudinal Schottky fluctuation noise signals from a cooled beam were studied. The fluctuation signals are distorted by the effects of space charge as was observed in earlier measurements at other facilities. However, the signal also exhibits previously unobserved coherent components. The ions' velocity distribution, measured by a laser fluorescence technique suggests that the coherence is due to suppression of Landau damping. The observed behavior has important implications for the eventual attainment of a crystalline ion beam in a storage ring. A significant issue is the transverse temperature of the beam -- where no direct diagnostics are available and where moiecular dynamics simulations raise interesting questions about equilibrium.

i. Laser-Cooled Bunched Ion Beam (J. P. Schiffer, J. S. Hangst,* J. S. Nielsen,* O. Poulsen,* and P. Shi*)

In collaboration with the Århus group, the laser cooling of a beam bunched by an rf electrode was investigated at the ASTRID storage ring. A single laser is used for uni-directional cooling, since the longitudinal velocity of the beam will undergo "synchrotron oscillations" and the ions are trapped in velocity space. As the cooling proceeds the velocity spread of the beam, as well as the bunch length is measured. The bunch length decreases to the point where it is limited only by the Coulomb repulsion between ions (see Figures I-45 and I-46). The measured length is slightly (20-30%) smaller than the calculated limit for a cold beam. This may be the accuracy of the measurement, or may indicate that the beam still has a large transverse temperature so that the longitudinal repulsion is less than would be expected from an absolutely cold beam. Simulations suggest that the coupling between transverse and longitudinal degrees of freedom is strong -- but this issue will have to be resolved by further measurements.

*Århus University, Denmark.

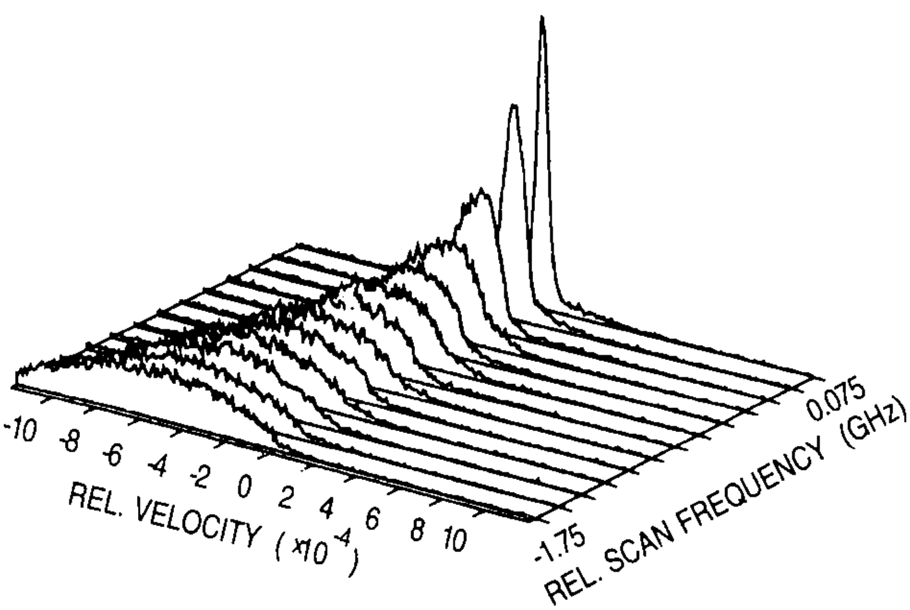

Fig. I-45. Velocity distributions measured by laser-induced fluorescence at various times during bunched-beam laser cooling. The center of each distribution is offset for clarity.

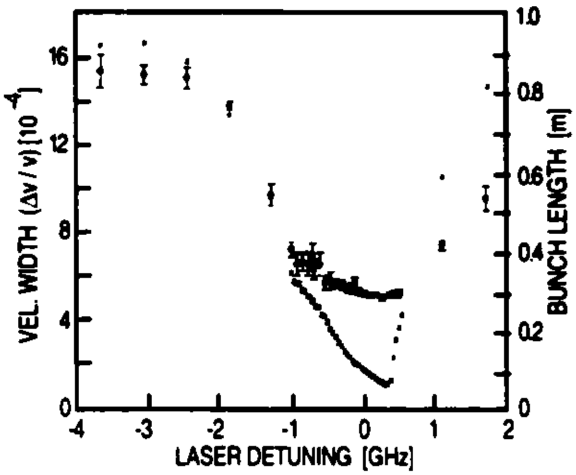

Fig. I-46. Longitudinal velocity spread (X's, left ordinate) and bunch length (dots, right ordinate) versus laser detuning, measured during a cooling scan. The laser is scanned past the optimum detuning, leading to the rise in temperature and bunch length at the right of the figure.

j. Half-Life of ^{44}Ti (I. Ahmad, W. Kutschera, G. Castagnoli,† and M. Paul‡)

The measurement of the ^{44}Ti half-life, started 3 years ago, is still continuing. The goal of this measurement is to determine the half-life of ^{44}Ti, which is ~ 52 y, to a precision of ~ 5%. An accurate value of this half-life is of interest to cosmologists who need it to determine the production of heavy elements in supernova. Three sets of samples - a pure 200-nCi ^{44}Ti sample, a pure 300-nCi ^{60}Co source, and a mixed ^{44}Ti-^{60}Co source of similar strength - were prepared and their spectra are being measured with Ge spectrometers at Argonne, Torino and Jerusalem. Each sample is counted for a period of 2 days, at approximate intervals of 4 months. The room background is also measured for the same length of time. We hope to start data analysis at the end of summer and obtain a value for the ^{44}Ti half-life.

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k. Internal Conversion in Highly-Stripped ^{83}Kr Ions (K. E. Rehm, I. Ahmad, J. Gehring, B. G. Glagola, W. Kutschera, J. Copnell,* W. R. Phillips,* and A. Barnett*)

The transition probability per unit time for the decay of a nuclear level via internal conversion (IC), λ_{IC}, depends on the electron environment of the nucleus. For example, inner-shell conversion in highly-charged ions can change appreciably as electrons are successively removed from the ion. Magnetic dipole (M1) transitions are especially sensitive to this effect since the internal conversion depends strongly on the electron density at the nucleus. Hence, measurements of $\lambda_{IC,q}$, the internal conversion rate in an ion with charge state q, can provide good tests of theoretical electron wave functions if the electron configuration in the ions is known.

In a previous experiment, a new method which identifies charge-changing events during passage of ion beams through a magnetic spectrometer was used to determine $\lambda_{IC,q}$ for the 14.4-keV isomer in ^{57}Fe. This contribution reports measurements made using the same technique for the 9.4-keV isomer in ^{83}Kr.

A beam of ^{83}Kr with energy 650 MeV bombarded a Au target with a thickness 300 μg cm^{-2}. Secondary scattered beams were accepted and analyzed by an Enge magnetic spectrometer. The numbers of excited nuclei decaying during passage through the spectrometer and their internal conversion rates were deduced from the pattern of events measured in the spectrometer focal plane.

*University of Manchester, United Kingdom.

For a comparison with theoretical prediction, calculations with the MCDF code GRASP were performed and good agreement between the experimental internal conversion values and the theoretical calculations were obtained for the charge states ranging from q = 28-32. For the q = 32 ions the agreement with the calculation for the $(1s)^2(2s)^2$ ground-state configuration is surprising.

For this charge state there exist long-lived electronic states with a vacancy in the 2s orbit and these should constitute a significant fraction of the $q = 32$ ensemble traversing the spectrometer. These results point to a new mechanism for quenching the ^3P levels in freely-moving Be-like Kr ions. A paper describing our measurements was submitted for publication.

l. The *PHOBOS* Experiment (R. R. Betts, *PHOBOS* collaboration*)

PHOBOS is an experiment designed to study Au-Au collisions at RHIC. The apparatus consists of a 4π multiplicity array and two spectrometer arms. The experiment is designed to measure the polar and azimuthal angles of most particles produced in the collisions and whether they are charged particles or photons. For approximately 1% of these particles, the two spectrometer arms will measure their properties in great detail. This includes many of the particles near mid-rapidity which are expected to show the most striking effects of any new physics which may occur. *PHOBOS* has proceeded from the Letter of Intent (1992) stage through Proposal (1992) and Conceptual Design Review (1994) to Construction Approval (1994). It is anticipated that data taking will commence in 1999 when RHIC first provides beam.

Two of the main physics goals of *PHOBOS* are the measurement of $dN/d\eta$ and the measurement of the π/γ ratio on an event-by-event basis. This will be accomplished with the multiplicity array for which the group from UIC has overall responsibility for design and construction. The multiplicity detector consists of an octagonal array of silicon strip detectors surrounding the beampipe in the region of the collision vertex and rings of silicon pad detectors positioned along the beampipe on either side of the collision vertex. These detectors cover the pseudo-rapidity range $-5.74 \leq \eta \leq +5.74$ and $0 \leq \varphi \leq 2\pi$ with more than 85% coverage. Near mid-rapidity, additional planes of higher segmentation strip detectors are used to determine the location of the collision vertex. The measurement of the charged/neutral ratio will be made by installing Pb radiators in front of the multiplicity detectors and counting the increase due to photon conversion in the Pb. An essential component of the multiplicity measurements is the readout of the energy deposition in each silicon element using electronics custom designed for the *PHOBOS* experiment. In this way, multiple hits in a silicon segment can be identified and correctly included in the derived multiplicity. At the time of writing, the design of *PHOBOS* is being studied in great detail using GEANT simulations with the aim of optimizing the final layout. The specifications of the silicon detectors for both the multiplicity/vertex detectors and the tracking planes in the spectrometers are being developed with the plan of starting preliminary procurement at the end of 1995. In this regard, the experience in the development and procurement of 1-mm thick silicon diodes for the APEX experiment will be very useful. Plans for the immediate future also include testing of prototype detectors and electronics with heavy ion beams at the BNL AGS.

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E. EQUIPMENT DEVELOPMENT AT THE ATLAS FACILITY

The Fragment Mass Analyzer (FMA) has been in routine operation for several years. In fact, about 50% of all experiments performed at ATLAS now utilize the device. As a result, a significant effort continues not only to maintain the device, but also to continuously upgrade its capabilities by the addition of new detectors and/or electronics. A substantial improvement to the implantation system was achieved: the information (energy and time) obtained from the double-sided silicon strip detectors is now provided through spectroscopy grade electronics. A large, segmented ion chamber was commissioned. Conversion electrons can now be measured at the FMA focal plane with silicon PIN diodes. Several modifications were also made to the various target chambers in order to accommodate demands of specific experiments. A new version of an ion-optics code was developed in order to be able to calculate with high accuracy the transmission characteristics of the FMA under various experimental conditions. The transmission was also checked carefully in a set of measurements.

The APEX experiment saw its first full year of data taking. During the year several modifications to the apparatus took place in order to optimize its capabilities. In particular, the cooling system of the silicon detectors was significantly upgraded and some detectors showing poor performance were replaced. Some parts of the electronics were modified to achieve better energy resolution. The rotating target wheel was modified by the installation of new bearings and a computer-controlled rotation and readout system was implemented.

In the Gammasphere project, the Physics Division took the responsibility for procuring and testing the BGO Compton suppressers, for the design and fabrication of the target chamber, and for part of the software development. Procurement of the BGO detectors proceeded smoothly and, in fact, ahead of schedule. All 110 detectors came through the Division and in excess of 100 were delivered for installation in the spectrometer. The remaining elements are those which did not meet the rather stringent specifications and were returned to the manufacturers for modifications. At the present time, there is every reason to believe that this task will be completed early, i.e. in the spring of 1995. The general-purpose scattering chamber was delivered to Lawrence Berkeley Laboratory and installed in the Gammasphere set-up when the changeover from the Early Implementation Phase to the so-called Phase 1 took place in October. Our software efforts are almost complete.

Other developments at ATLAS include the improvement of the electronics for an array of double-sided Si strip detectors and the successful use of the gas-filled magnet technique at the spectrograph in measurements with radioactive ^{18}F ions. Finally, the replacement of the DAPHNE front-end electronics in the data-acquisition system at ATLAS by the front-end of the Michigan State University data-acquisition system progressed significantly during the year. A first experiment used the new system during the year and preparations for a full switch to this new system continued so that this operation is now scheduled for April 1995.

a. Fragment Mass Analyzer Project (C. N. Davids, B. B. Back, D. J. Blumenthal, D. J. Henderson, and H. T. Penttilä)

The FMA is now in routine operation, with about half the ATLAS experiments using the instrument. The beam time is split equally between target and focal-plane experiments.

New spectroscopy-grade electronics for the FMA implantation system were acquired. This consists of 96 charge-sensitive preamps, 192 Gaussian shaping amplifier/discriminators, 96 channels of high-resolution ADCs, and 96 channels of medium resolution ADCs. This system is currently undergoing commissioning tests, and will be used in future proton radioactivity experiments.

Several experiments were conducted on the FMA in which inverse kinematics were used. In the first case, the decay of the N = Z isotope ^{68}Se was studied using the ^{12}C(^{58}Ni,2n)^{68}Se reaction and the moving tape collector. The excellent mass resolving power of the FMA allowed only A = 68 recoils to be implanted on the tape, and subsequent gamma- and beta-coincidence measurements were made on this weakly produced isotope. A second experiment showed that the FMA is an ideal tool to study inverse radiative proton capture reactions. The ^{1}H(^{13}C,^{14}N)γ reaction was studied at a resonance near 0.5 MeV/u. The addition of apertures between the bending magnet and each of the FMA electric dipoles enabled a preliminary separation of the recoils from the primary beam on the basis of both energy and mass. This produced a final primary beam attenuation ratio at the focal plane of 3×10^{-11}. The addition of an energy-loss/residual energy measurement behind the focal plane resulted in a further attenuation of several orders of magnitude.

H. Penttilä from the University of Jyväskylä in Finland returned to his home institution. He was replaced by D. Seweryniak from Poland in a postdoctoral position. He is jointly funded by ANL and the University of Maryland. K. Bindra (Vanderbilt University) received his Ph.D for research on the FMA. L. Brown (Vanderbilt U.), B. Busse (Oregon State University), and L. Contticchio (University of Maryland) joined the FMA group as students. R. Hermann (Technical University, Munich) completed his Diplomarbeit and returned to Germany.

b. Modification of the Ion-optics Code GIOS89 (C. L. Jiang and C. N. Davids)

The general ion-optics code GIOS is a very powerful and useful program for calculating the ion optics of an electromagnetic system. It was used extensively in the design and operation of the Fragment Mass Analyzer (FMA).

In the original version of the program a feature is described which allows the initial beam density to be varied with angle, energy, mass, or position. In fact, this feature was never implemented, and only isotropic beam densities are available. In order to make more reliable calculations of reaction yields and FMA transport efficiencies, it is important to be able to use more realistic beam density distributions.

A modification to the ANL version of GIOS was developed in which several different kinds of initial beam densities (like Gaussian distributions, numerical distributions etc.) can be used. The new version of GIOS was used in several experiments where the absolute transport efficiency of the FMA must be known. In an experiment designed to check these calculations by the Rutherford scattering of ^{32}S from ^{184}Pb and ^{232}Th (see next section), the measured data agree well with the calculated efficiencies.

Some features were added to the graphical outputs from GIOS. One may now combine different charge/mass/energy components into a single plot.

c. Measurements of the Transport Efficiency of the Fragment Mass Analyzer
(B. B. Back, D. J. Blumenthal, C. N. Davids, D. J. Henderson, R. Hermann, D. J. Hofman, C. L. Jiang, H. T. Penttilä, A. H. Wuosmaa, and P. Paul*)

Extensive calculations of the transport of reaction products were carried out during the design phase of the instrument using the computer code GIOS. These show that the energy acceptance depends strongly on the angular deviation from the optical axis of the instrument. In order to reliably measure cross sections using this instrument it is therefore necessary to verify these calculations empirically.

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This was done using the following approach. Using ^{32}S-beams with far sub-barrier energies of 50, 80, and 110 MeV from ATLAS incident on targets of ^{184}W, ^{208}Pb and ^{232}Th, backward scattered beam particles give rise to target recoils emerging at forward angles with known (Rutherford) cross sections. The transmission of these through the FMA may then be used to determine the transport efficiency of the instrument. Different entrance apertures were used to sample the dependence on the entrance angle into the instrument. One is the so-called "full" aperture, which subtends entrance angles of ± 2 1/4° in both the horizontal and vertical directions resulting in a Ω_{full} = 6.24 msr solid angle. This solid angle was subdivided into nine equal sections, and the transmission probability was measured for four of these using smaller apertures. The three apertures centered in the horizontal plane containing the beam axis, denoted the "left", "center" and "right" apertures, served to probe the dependence of the transmission probability on the horizontal entrance angle, θ_x, into the instrument. The "top" aperture is expected to yield results very similar to those obtained for the "center" aperture since the transmission probability is very weakly dependent on the vertical entrance angle, θ_y. In order to avoid many beam energy changes to map out the energy dependence we change instead the field settings for the FMA to correspond to a number of different particle energies. This is possible since the theoretical transmission probability depends only on the ratio of the particle energy to the energy setting of the FMA. Finally, in order to derive a transmission probability, we measure the complete distribution of charge states and make small corrections for detector inefficiencies at the focal plane.

We found the expected result that energy acceptance for the smaller apertures (left, center, right) reach 100% over a relatively extended range of energy settings, ±15% around a central value. As expected, lower energy settings are required for recoils entering through the right aperture to be transmitted to the focal plane in order to avoid striking the cathode of the first electric dipole (ED1). On the contrary, higher-than-average energy settings are required for transmitting recoils entering the left aperture, to avoid striking the anode of ED1.

We also observe that the transmission through the full entrance aperture only reaches a maximum of about 80%. That 100% efficiency is not reached with this aperture arises from the fact that there is no energy setting for which there is full transmission for all three partial apertures. The fact that 100% transmission through the FMA is observed on an absolute scale over the theoretically expected range of energy settings, reinforces the confidence in the theoretical calculations for the instrument. We are therefore confident that absolute cross sections can be determined with the instrument using these measurements and theoretical simulations for the transmission efficiency of the instrument.

The results of this work are being prepared for publication.

d. Rotating Target Wheel for the FMA (B. B. Back, C. N. Davids, J. Falout, B. Nardi, J. Green, and W. Chyna)

In anticipation of high intensity beams that will be available from the PII-ECR source injector to ATLAS, a new rotating target wheel was developed for the sliding seal chamber at the FMA. The wheel is 9" in diameter and contains up to ten targets. The rotation of the wheel is achieved by a DC motor, a ferrofluidic feedthrough, and a gear mechanism that allows both target rotation and changing the target angle relative to the beam. The nominal rotation speed is 1000 RPM, although higher speeds can be achieved if necessary. The assembly is equipped with an absolute encoder which is read out via a newly developed CAMAC module. This module provides the following main functions: 1) a TTL signal to be used for sweeping the beam when a target frame is about to pass through the beam, 2) a read-out of the target position that can be included in the data event structure, 3) programmable set points for the beam-off signal. The system is presently being tested and will be used in experiments scheduled for March 1995.

e. Commissioning of a Large Segmented Ion Chamber for the FMA
(C. J. Lister, C. N. Davids, D. J. Blumenthal, W. Gelletly,* D. D. Warner,† and R. Cunningham†)

A large-area sectored ion chamber was built by a Yale-Daresbury (U.K.) - ANL collaboration to allow extensions of studies of N = Z (T = 0) nuclei. The ion chamber is a conventional DE-DE-E detector which is 20-cm deep, but each anode is segmented into eight pads to allow high count-rate capability and ray-trace reconstruction. With suitable electronics, the detector can become eight close-packed ion chambers, considerably reducing the count rate in each. A position-wire plane allows further raytracing which should permit the rejection of anomalous trajectories and improve Z-separation.

A brief test run was scheduled shortly after delivery. Performance appeared promising, but issues of gain matching and cross talk need further exploration. We will study these features "off line" and hope to perform a full experiment on selenium isotopes in the summer.

This detector appears to have many uses and is potentially more useful than previous detectors of its type. Similar detectors are being built for the HHRF at Oak Ridge and for Texas A&M University.

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*University of Surrey, †Daresbury Laboratory, U.K.

f. Improvements to the APEX Apparatus (I. Ahmad, B. B. Back, R. R. Betts, R. W. Dunford, W. Kutschera, C. J. Lister, M. D. Rhein, J. P. Schiffer, P. Wilt, M. Wolanski, A. H. Wuosmaa, S. M. Austin,† F. P. Calaprice,‡ K. C. Chan,§ A. Chishti,§ P. Chowdhury,§ C. Conner,*** J. D. Fox,¶ S. J. Freedman,ll M. Freer,** S. Gazes,†† J. S. Greenberg,§ A. L. Hallin,‡‡ T. Happ,§§ N. Kaloskamis,§ E. Kashy,†,§ M. Liu,‡‡ M. R. Maier,ll A. Perera,¶¶ E. Roa,¶ T. Trainor,llll J. S. Winfield,† F. L. H. Wolfs,¶¶ G. Xu,§ A. Young,‡ and J. E. Yurkon†

A number of technical issues led us to rework extensively the APEX apparatus in summer 1994. During the earlier runs, a significant fraction of the 432 silicon detector elements showed degraded resolution such that they had to be excluded from the final analysis in software. The effect of this is to reduce the efficiency of APEX and possibly also to introduce holes in the acceptance which, for some perhaps exotic scenarios, might reduce the acceptance to an unacceptably low level. Also, the energy thresholds below which it is not possible to generate timing information from the silicon detectors, were high enough that the low-energy acceptance of APEX was compromised to a significant extent. The origins of these difficulties were in part due to degraded performance of the silicon detectors themselves, problems with the silicon cooling systems and electronics problems. Both silicon arrays were disassembled and sub-standard detectors replaced, all detectors were also cleaned with the result that all detectors now performed at the specified values of leakage current. The silicon cooling systems were disassembled and rebuilt with the result that many small leaks were fixed. Defective electronics channels were repaired or replaced. The rotating target wheel was also improved with the installation of new bearings and a computer-controlled rotation and readout system. The rebuilt wheel can now run at speeds up to 900 rpm for weeks on end without breakdown. The target wheel and associated beam sweeping now work extremely well so that low-melting-point targets such as Pb and In can be used in quite intense beams without melting.

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†Michigan State University, ‡Princeton University, §Yale University, ¶Florida State University, llUniversity of California, Berkeley, **University of Birmingham, United Kingdom, ††The University of Chicago, ‡‡Queen's University, Kingston, Ontario, §§GSI, Darmstadt, Germany, ¶¶University of Rochester, llllUniversity of Washington ***University of Illinois at Chicago.

g. Gammasphere Activities at Argonne (T. L. Khoo, M. Carpenter, I. Ahmad, J. Falout, R. V. F. Janssens, T. Lauritsen, and D. Visser*)

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- (≥ 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 have made substantial contributions in its construction. In addition, 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, while 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 36 Compton-suppressed spectrometers) and the final phases.

Procurement of BGO detectors proceeds smoothly and was completed, with all 112 detectors delivered on schedule. Testing of these detectors represented our present major effort. Stony Brook also made a substantial contribution in the testing. The final-phase scattering chamber was designed and constructed at ANL and is now being used in experiments. Our software effort is about 85% complete and is particularly effective because it is performed by a physicist who understands the requirements of experiments.

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 measurements of the combined performance of the Ge and BGO detectors as a Compton-suppressed spectrometer; (iv) developing software methods to correct for ballistic deficit and charge trapping at neutron-damaged sites in Ge detectors; (v) participating strongly in development of the detector configuration, electronics, computer hardware/software, and mechanical support design of Gammasphere - for example we proposed the electronic-honeycomb design; (vi) continuing to suggest ways to improve the performance of Gammasphere , e.g. to avoid the degradation due to neutrons and a segmented readout scheme for coaxial Ge detectors; 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 was published and one on correcting for charge deficit in Ge detectors is being prepared.

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h. Target Chambers for Gammasphere (M. P. Carpenter, J. W. Falout, B. G. Nardi, I. Ahmad, R. V. F. Janssens, T. L. Khoo, and T. Lauritsen)

One of our responsibilities for Gammasphere, was designing and constructing two target chambers and associated beamlines to be used with the spectrometer. The first chamber was used with the early implementation phase of Gammasphere, and consisted of two spun-Al hemispheres welded together giving a wall thickness of 0.063 inches and a diameter of 12 inches.

The second chamber was built this past year and is currently in use at Gammasphere. The chamber consists of a 14-inch diameter sphere which takes up most of the space available between the target and heavymet shielding. Limited access to the inside of the chamber comes from the side, where a six-inch opening is available. An additional five ports are placed on the chamber and located at pentagon positions which are out of view of all Ge detectors. Two of these ports attach to the beamlines, and another is attached to a support strut located on the bottom half of the sphere, 28° from vertical. A target drive with a 14-inch travel is mounted inside the support strut and controlled remotely. Information on the position of the target drive is supplied by an absolute encoder attached to the end of the stepping motor. The motor controller was designed and built in house by the technical support group. There is also a port located directly opposite the support port which allows for the target ladder to be driven through it in order to mount or detach the target ladder from outside the chamber. The target ladders are easily detachable from the target rod, and two designs exist which allow for mounting of 6 ANL or 4 LBL target frames. The fifth port is used for viewing the target. None of the feedthroughs are permanently attached to the sphere, which allows the user to design experiment-specific feedthroughs to meet the particular needs of his experiment.

i. Testing of the BGO Compton-Suppression Detectors for Gammasphere (M. P. Carpenter, I. Ahmad, G. A. Annan, D. Gassmann, S. Harfenist, R. V. F. Janssens, T. L. Khoo, and D. Visser)

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 consists 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 assumed responsibility for the procurement and testing of the BGO Compton-suppression units. We received all detectors from the two vendors. In the past year, twenty-four of the B-type detectors were delivered to Stony Brook for evaluation tests. Since the number of crystals to test is quite large (six per detector), we involved undergraduate students working at ANL under the Department of Educational Programs (DEP) in this effort. The quality of students was excellent, and they played a major role in the performance testing of these detectors.

Ninety-nine of the hexagonal side shields and 112 backplug detectors were shipped to LBL for use in Gammasphere. The remaining detectors did not meet the performance criteria when they were first delivered and tested and are either at the vendor being repaired or were returned to us for retesting. We anticipate that the remaining detectors will be ready for use in Gammasphere within the next few months.

j. Software Developments for Gammasphere (T. Lauritsen, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, and T. L. Khoo)

This year marked the year when data acquisition development for Gammasphere evolved from planning to accomplishment, both in hardware and software. Two VME crates now contain about 10 crate-processors which are used to handle the data from VXI processors - which in turn collect the data from germanium and BGO detectors in the array. The signals from the detectors are processed and digitized in custom-built electronics boards. The processing power in the VME crates is used to digitally filter the data before they are written to tape. The goal is to have highly processed data flowing to tape, eliminating the off-line filtering and manipulation of data that was standard procedure in earlier experiments.

We were involved in the specification, development and testing of software in these front-end filter processors. We also set some standards for the event structure and provided all of the software for the calibration of the array. The calibration is now done through user-friendly Tcl/Tk scripts that allow the users of the array to do all calibrations with a simple click of a button. These scripts have built-in help menus. Several new innovative methods were developed for a precise calibration of the germanium high-resolution signals. New techniques are also available for the adjustments of such parameters as: the high voltages of the BGO detectors, the walks of the discriminators for the germanium detectors and the thresholds of discriminators associated with all detector signals. In addition, we are now providing the event-data structure information on the World-Wide Web. Thus, it is easy for users to get the documentation they need to read the data on the 8-mm tapes produced by the Gammasphere data-acquisition system. We also developed a general-purpose tape reader routine, which is provided on the Web. Anyone can download this software and start a data sort in a very short time.

Final online debugging of the software is now in progress using up to 5 BGO/germanium VXI boards servicing 10 detector systems. The debugging is often done by sending data from the front-end-filter formatters directly over internet to a workstation at ANL where the data is received and sorted. In addition, off-line analysis of the detector signals is in progress here at ANL, using some of the first tapes generated by the new Gammasphere data-acquisition system. In particular, we are testing the use of a trap correction signal from the germanium detectors. This additional signal will allow us to improve the resolution of the detectors and thus boost significantly the overall resolving power of the instrument.

k. Software Developments for Gamma-Ray Data with High Multiplicity

(T. Lauritsen, B. Crowell, I. Ahmad, M. P Carpenter, R. G. Henry, R. V. F. Janssens, T. L. Khoo, and D. Nisius)

Software capabilities for angle sort of data from the new powerful gamma detector arrays like Gammasphere and EUROGAM which were developed in preceding years, were enhanced and extended to read new data formats. In addition, we can now sort the data for directional correlation ratios (DCO). This version of the software was exported to a university group. For the analysis of, e.g., the quasi-continuum of gamma-rays it is necessary to angle sort the high multiplicity data and perform a careful background subtraction in order to extract the continuum of gamma rays from the feeding and decay of superdeformed bands. We need to angle sort in order to untangle the parts of the spectra which are of E1 nature from those of quadrupole or of M1/E2 nature.

We further developed software running on new fast SUN workstations. We now have two such workstations, each equipped with a stacker and a secondary 8-mm tape drive. We enhanced the software to apply an energy-dependent time gate. We can enhance the events that are in true prompt coincidence, and reject random and signals in the germanium detectors coming from neutrons hitting the detector in coincidence with the gamma-ray burst. By applying energy-dependent time gates, in form of a "reduced time", we can perform this rejection without the loss of efficiency at low energy.

Effort has gone into developing low-level tape reader routines for data from the new EUROGAM array with cluster detectors as well as from the new flexible data format from Gammasphere phase II. In addition, we developed software to read data tapes from the local DAPHNE and MSU data-acquisition systems on the new fast UNIX platforms.

ℓ. Status of the Argonne-Notre Dame BGO Gamma-Ray Facility at ATLAS (R. V. F. Janssens, D. J. Blumenthal, M. P. Carpenter, B. F. Crowell, J. W Falout, J. M. Joswick, T. L. Khoo, R. G. Henry, T. Lauritsen, J. P. Timm, P. R. Wilt, and D. T. Nisius)

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.

-- Because of neutron damage, annealing was performed on eight Ge detectors. Three of these were annealed twice. The performance of the detectors was recovered in all but one case. In the latter, the FET was lost and the detector was returned to the manufacturer for repair.

-- 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).

-- 10 of the CSGs were moved to the FMA for long periods of time on three different occasions and were used in conjunction with this device. Such a move takes about 1 day, does not require that the Ge detectors be warmed up, and has not resulted in any noticeable loss in performance of the CSGs.

-- A new dedicated target chamber was designed and constructed. This chamber allows us to place a target upstream from the usual location, outside of the array. In this way it is possible to study decays from isomers after recoil from the target into a stopper located at the focus of the γ-ray facility.

m. Upgrade of the Area II Spectrograph (K. E. Rehm and C. Bolduc)

Because of the low beam energies required for experiments of astrophysical interest, the first test experiments with radioactive ^{18}F beams can be performed in Area II. Because of the shorter distances between ion source and detector this also results in higher transmission efficiencies. The Enge split-pole spectrograph, which was not used during the last 8 years, was equipped with a new cryopump system, upgrades to the magnet power supply and the NMR system were performed. A rotating target system was built which should alleviate target deterioration effects that were observed in first test experiments.

n. Use of the Gas-Filled-Magnet Technique for Particle Identification at Low Energies (K. E. Rehm, C. L. Jiang, and M. Paul*)

Reaction studies of interest to astrophysics with radioactive ion beams will be done mainly in inverse reaction kinematics, i.e., heavy particles bombarding a hydrogen target. The low energy of the outgoing heavy reaction products makes particle identification with respect to mass and nuclear charge a major challenge. For the planned ^{18}F(p,α) experiment one expects five different types of particles in the outgoing channels: ^{18}F and ^{18}O (from elastic scattering of ^{18}F and ^{18}O on ^{12}C), ^{15}O and ^{15}N (from the ^{18}F and ^{18}O induced (p,α) reactions) and ^{12}C recoils from the polypropylene target. While mass determination can be achieved easily by time-of-flight (TOF) measurements, a determination of the nuclear charge presents a challenge, especially if the energy of the particles is below 500 keV/u. We studied the gas-filled magnet technique for Z-identification of light ions between Z = 6-9. In a gas-filled magnet the particles move with an average charge state $\bar{q}$ which in one parameterization is given by $\bar{q} = Z \ln(avZ^{\alpha})/\ln(bZ^{\beta})$ where Z is the nuclear charge of the ions and v their velocity. Introducing $\bar{q}$ into the expression for the magnetic rigidity $B_\rho = mv/\bar{q}$ results in a Z dependence of B_ρ which is valid to very low velocities. As a magnet we used the Enge split-pole spectrograph which was filled with nitrogen gas at a pressure of 0.5 Torr. The particles were detected in the focal plane with a 50 × 10 cm^2 parallel-grid-avalanche counter which measured TOF and magnetic rigidity. The mass and Z separation was tested with ^{13}C and ^{18}O beams at energies of about 600 keV/u and recoil particles ranging from ^{12}C to ^{19}F. The Z-separation obtained at these energies was $\Delta Z/Z \approx 0.28$ which is sufficient to separate individual elements for Z < 10. RAYTRACE calculations, which in a Monte Carlo treatment take charge-changing collisions, energy-loss and straggling effects into account, are in good agreement with the experimental data. A publication describing these results is being prepared.

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o. Construction and Test of a Small Parallel-Grid-Avalanche-Start Detector for the Split-Pole Spectrograph (D. Henderson, D. Blumenthal, C. L. Jiang, K. E. Rehm, and M. Paul*)

For mass and Z-identification in a planned experiment with ^{18}F beams, the method of a gas-filled magnet will be used. In this technique ions with different nuclear charge Z traveling through a gas-filled volume obtain a different magnetic rigidity, which can be used for Z-identification of very slow ions. Mass identification is obtained via time-of-flight. Since the experiment is being performed with a DC beam, a start detector for time-of-flight measurements is required. For this purpose a small (10 × 10 mm^2) parallel-grid-avalanche-counter (PGAC) was designed which is mounted directly on the sliding seal of the scattering chamber. In order to minimize the number of foils a particle has to penetrate, the start detector also serves as a pressure foil, separating the gas in the magnet from the vacuum in the scattering chamber. The detector, which has only two 120-$\mu g/cm^2$ polypropylene foils, was tested in an experiment with ^{13}C ions. The measured time resolution was limited by straggling effects in the gas of the magnet and only an upper limit for the intrinsic time resolution of the detector of 1 nsec could be obtained. The detector was used successfully in the first experiments with ^{18}F beams.

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

The Physics Division operates a target development laboratory that produces 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 by vacuum evaporation either as self-supporting foils or on various substrates. Targets produced included Ag, Au, $^{10,11}B$, ^{138}Ba, Be, ^{12}C, ^{40}Ca, ^{116}Cd, $^{155,160}Gd$, ^{76}Ge, In, LiD, ^{6}LiH, Melamine, Mg, $^{142,150}Nd$, ^{58}Ni, $^{206,208}Pb$, ^{194}Pt, ^{28}Si, $^{144,148}Sm$, $^{120,122,124}Sn$, Ta, ^{130}Te, ThF_4, $^{46,50}Ti$, TiH, U, UF_4, ^{182}W and ^{170}Yb. Polypropylene and aluminized polypropylene, along with metallized Mylar were produced for experiments at ATLAS. A number of targets of ^{11}B of various thickness were made for the DEP 2-MeV Van de Graff accelerator. An increased output of foils fabricated using our small rolling mill included targets of Au, C, ^{50}Cr, Cu, $^{155,160}Gd$, Mg, ^{58}Ni, ^{208}Pb, $^{105,110}Pd$, Sc, Ti, and $^{64,66}Zn$.

Support is continuing for APEX, now fully instrumented, as the experimental program has increased dramatically. Large quantities of foil targets were prepared by rolling, mainly 1-mg/cm^2 Ta and ^{232}Th foils. Large data sets were collected from experiments employing beams of uranium on these tantalum and thorium foils. A large effort was required to prepare 300-$\mu g/cm^2$ ThF_4 and UF_4 targets, as well as ^{206}Pb targets for experiments at APEX. Testing of the target wheel system was also performed, encompassing a wide variety of targets.

Rolling has become the method of choice for most targets used in experiments being performed at the FMA, where the required surface densities range from 0.5 to 0.7 mg/cm^2 and even up to 1 mg/cm^2. In addition to targets, numerous carbon reset foils are prepared by the target lab. FMA and APEX account for about one half of target production for the year.

With Gammasphere becoming operational, there has been an increase in target requests for experiments using this apparatus. Targets of $^{155,160}Gd$ and ^{130}Te targets were used for Argonne collaborations at Gammasphere. Sandwiched targets of Au-^{150}Nd-Au were successfully prepared and transported under vacuum to Berkeley for experiments. Targets supplied for other institutions included ^{10}B, ^{142}Nd and ^{144}Sm.

In all, approximately 1000 targets were prepared for various experiments during the past year.

As part of ATLAS support, carbon stripper foils of 2 $\mu g/cm^2$ for use in the tandem as well as 50, 60 and 70-$\mu g/cm^2$ carbon foils for secondary stripping were produced. Approximately 2000 stripper foils of various types were prepared during 1994. As ATLAS is now on a 7-day schedule, this accelerator support will undoubtedly increase.

One other project worthy of mention involved the coating of over forty photomultiplier tubes with p-terphenyl scintillator and then overcoated with MgF_2 using the multiple-pocket electron beam source. These tubes were needed as part of the Argonne-built Cerenkov counters used at HERMES.

The target development laboratory includes state-of-the-art equipment used for thin-film deposition. The available techniques consist of multiple resistive heating, focused 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.

A wide-beam Saddle Field Ion Source was put into operation for ion milling applications. This source will provide increased sputtering rates during target depositions.

Auxiliary equipment used for target development includes a glow discharge apparatus, a small rolling mill, an alpha-particle film-thickness measurement set-up (see below), inert atmosphere glove box, laminar flow clean bench, a hydrogen reduction furnace, and a variety of precision balances.

Personal computing is used extensively for a number of purposes. We obtained a 386 IBM clone system and are able to run Windows-based applications. File archives maintained on this system include all targets produced, dating back to 1978. An INTDS bibliography database is available on-line for literature searches. Computer listings can be generated for inventories of all stable isotopes and chemicals maintained by the target lab. A spectroscopy system employing an internal ADC board allows for acquisition and analysis of alpha particle energy-loss measurements needed for film thickness determinations.

A target storage facility is in operation for maintaining those targets which can readily oxidize in air under high vacuum. This system is installed at ATLAS in Area II for the storage of air-sensitive targets which were activated by the beam and need to remain within the controlled Area of ATLAS.

This system utilizes a turbo pump and employs computer-controlled circuitry to prevent targets from exposure to atmosphere during power interruptions. A second turbo-pumped chamber, located in the target laboratory, is used routinely for target storage. This system uses an electronic control system for preserving the targets under high vacuum.

Also employed for vacuum storage is a bank of vacuum desiccators connected to a mechanically-pumped manifold for use by individual experimenters. The mechanical pumping system includes an emergency shut-off valve which prevents venting of the desiccators to atmosphere during power interruptions. A second, similar system was built and is currently in use at ATLAS for storage of targets which were activated by the beam during experiments. This system is capable of venting to argon.

The low-level radioactive target laboratory dedicated to the production of radioactive target foils was used extensively this year mainly in preparation of targets for APEX. The small rolling mill wastemporarily relocated to this laboratory for the production of 1-mg/cm^2 ^{232}Th targets. This radioactive target lab also prepared the many UF_4 and ThF_4 targets employed at APEX.

q. Physics Division Computer Facilities (D. R. Cyborski and K. M. Teh)

The Physics Division maintains several computer systems for data analysis, general-purpose computing, and word processing. While the VMS VAX clusters are still used, this past year saw a greater shift to the Unix Cluster with the addition of more RISC-based Unix workstations.

The main Divisional VAX cluster which consists of two VAX 3300s configured as a dual-host system serves 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. There are three 6250/1600 bpi 9-track tape drives, six 8-mm tapes and about 9.1 GB of disk storage 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. Since the tape drives are accessible cluster-wide via a software package, they are, in addition to replay, used for tape-to-tape copies. There is however, a satellite node outfitted with two 8 mm drives available for this purpose. Although not part of the main cluster, a DEC 3000 Alpha machine obtained for data acquisition is also available for data replay. In one case, users reported a performance increase by a factor of 10 when using this machine.

Support for PC users was improved with the acquisition of a "roving" tape backup unit.

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

The Medium-energy physics group operates a VAXcluster consisting of DEC Alpha 3000/300X OpenVMS workstations, a VAXstation 4000/mod 90, one VAXstation 3200, one VAXstation 3100, and a MicroVAX II. The MicroVAX II is equipped with a 9-track tape drive and a DAPHNE data-acquisition system.

The ATLAS and Dynamitron VAX-11/750s 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. The VAX 4000 acquired as a dedicated acquisition computer for the APEX experiment was also improved with added memory, an additional tape drive and more hard disk storage. It is also being used heavily for data replay.

In addition to the VMS VAX clusters, the Division also maintains three Unix clusters. The Theory Group has two IBM RS/6000 workstations which serve several X-windows terminals. The

Medium-energy Group has two Silicon Graphics workstations which are used for data analysis and a Sun IPX Sparcstation which is used for CAD/CAM.

The Division's main Unix cluster was expanded with additional workstations. It now consists of 6 DEC Alpha 3000/300 machines and 4 Sun Sparcstations. The cluster hosts 7 X-terminals providing a total of 17 seats for computing. It is used primarily for general computing, data analysis and simulation studies. Work continues to improve and streamline the administration of such a diverse set of machines.

r. Data-Acquisition Systems (D. R. Cyborski and K. M. Teh)

Up to now, DAPHNE, the data-acquisition system developed for ATLAS, was used routinely for experiments at ATLAS and the Dynamitron. More recently, the Division implemented 2 MSU/DAPHNE systems. The MSU/DAPHNE system is a hybrid data-acquisition system which combines the front-end of the Michigan State University (MSU) DA system with the traditional DAPHNE back-end. The MSU front-end is based on commercially available modules. This alleviates the problems encountered with the DAPHNE front-end which is based on custom designed electronics. The first MSU system was obtained for the APEX experiment and was used there successfully. A second MSU front-end, purchased as a backup for the APEX experiment, was installed as a fully-independent second MSU/DAPHNE system with the procurement of a DEC 3000 Alpha host computer, and was used successfully for data-taking in an experiment at ATLAS. Additional hardware for a third system was bought and will be installed. With the availability of 2 MSU/DAPHNE systems in addition to the existing APEX setup, it is planned that the existing DAPHNE front-end will be decommissioned.

F. ASSISTANCE TO OUTSIDE USERS OF ATLAS

B. G. Glagola

There is continuing strong interest by outside users in doing research at ATLAS, with outside users involved in about 95% of all experiments performed in FY 1994. The user assistance program is essential in facilitating effective performance of research by outside scientists.

The outside user involvement continued to increase from that in FY 1993 as evidenced by the large increase in operating hours due to 7-day operation of ATLAS for research. A user liaison physicist continues to play a key role in channeling assistance to outside users. The major components of his responsibility are: (1) to provide users with technical information about ATLAS and its experimental systems, and to provide instruction in its use; (2) to assist outside users in all aspects of initiating and planning an experiment; (3) to provide the needed information and organizational assistance to committees, workshops, and other meetings involving outside users; (4) to instruct the users in the safety procedures to be followed when using the ATLAS facility; (5) to the extent that is appropriate and feasible, to assist users in the actual performance of experiments; (6) to provide instruction and help with the use of computer hardware and software; (7) to assist in coordinating the operation of the technical support group; and (8) to provide an interface between the user and the technical support and ATLAS operation groups.

Two PAC meetings were held during FY 1994. The Program Advisory Committee (PAC) for ATLAS (nominally consisting of six members from other institutions and two from Argonne) continues to meet regularly during the year. PAC meetings were held on January 21-22, 1994 and July 8-9, 1994 to recommend experiments for running time at ATLAS. In FY 1994 the PAC members were Cary Davids (ANL), Teng Lek Khoo (ANL), Paul Kienle (GSI), Christopher J. Lister (Yale University), Mark A. Riley (Florida State University), Michael Wiescher (University of Notre Dame), Frank Wolfs (University of Rochester), and Linda Young (ANL). The Committee is chaired by John Schiffer (ANL). The PAC reviewed 35 proposals for 154 days of running time and 30 proposals for 150 days of running time at the meetings, respectively. The demand for running time at ATLAS continues to be about twice the time available on the accelerator.

The ATLAS User Executive Committee organized a User Group meeting during the October 1993 Division of Nuclear Physics APS meeting held in Asilomar, California. The meeting was attended by approximately 35 scientists. The main topics of discussion were the FMA project, the status of ATLAS and APEX, and the positron experiment at ATLAS. In FY 1994 the ATLAS Executive Committee consisted of Stephen Sanders (University of Kansas), Christopher J. Lister (ANL), Robert McGrath (SUNY at Stony Brook), and Frank Wolfs (University of Rochester), as Chairperson.

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

a. Experiments Involving Outside Users

All experiments in which outside users participated during FY 1994 are listed below. The spokesperson for each experiment is given in square brackets after the title. The names in parentheses are Argonne collaborators.

(1) Study of $^{18}F/^{18}O$ Induced Reactions at E<1 MeV [Rehm]
M. Paul, Hebrew University; C. L. Jiang, Institute of Atomic Energy, Beijing; J. C. Gehring, University of Chicago; (K. E. Rehm, J. P. Schiffer, J. Nolen)

(2) Sub-Barrier Fusion Cross Sections in the System $^{58,64}Ni + ^{78,86}Kr$ [Rehm]
C. L. Jiang, Institute of Atomic Energy, Beijing; J. C. Gehring, University of Chicago; (K. E. Rehm, A. H. Wuosmaa, B. G. Glagola, M. Rhein, B. Crowell, R. Henry)

(3) Probing the Proton Drip Line for Z>50 [Davids]
W. B. Walters, L. Conticchio, University of Maryland; K. Bindra, A. Ramayya, University of Vandersbilt; P. Woods, R. Page, University of Edinburgh; C. Bingham, B. Zimmerman, J. Richards, University of Tennessee; K. Toth, Oak Ridge National Laboratory; C. L. Jiang, Institute of Atomic Energy, Beijing; (C. N. Davids, H. Penttilä, D. J. Henderson, A. H. Wuosmaa, R. R. Betts, B. B. Back, R. Hermann)

(4) Heavy Element Production through Fusion Reactions Using the FMA [Henning]
L. Conticchio, University of Maryland; C. Jiang, Institute of Atomic Energy, Beijing; K. Bindra, Vanderbilt University; (W. F. Henning, C. N. Davids, D. Henderson, K. E. Rehm, A. H. Wuosmaa, H. Penttilä, R. Hermann, B. B. Back)

(5) FMA Silicon Detector Test [Back]
C. L. Jiang, Institute of Atomic Energy, Beijing; D. Hofman, SUNY, Stony Brook; (B. B. Back, C. N. Davids, D. J. Henderson, T. Lauritsen, A. H. Wuosmaa)

(6) APEX Beam Tests [APEX]
S. M. Austin, E. Kashy, J. S. Winfield, J. E. Yurkon, Michigan State University; A. Perrera, F. L. H. Wolfs, University of Rochester; S. Gazes, M. Wolanski, University of Chicago; J. Greenberg, K. C. Chan, N. Kaloskamis, A. Chishti, Yale University; A. L. Hallin, M. Liu, Queens University; T. Trainor, University of Washington; J. D. Fox, E. Roa, Florida State University; T. Happ, GSI; M. Freer, University of Birmingham; C. Conner, University of Illinois, Chicago; D. Bazin, GANIL; S. J. Freedman, M. R. Maier, Lawrence Berkeley Laboratory; F. P. Calaprice, A. Young, Princeton University; (R. R. Betts, A. H. Wuosmaa, W. Kutschera, B. B. Back, J. P. Schiffer, I. Ahmad, D. J. Henderson, C. J. Lister, R. W. Dunford, M. D. Rhein, P. Wilt)

(7) Fission, Fusion, Subshells and Hyperdeformation in the ^{180}Hg Region [Walters]
W. B. Walters, L. Conticchio, University of Maryland; R. Page, University of Edinburgh; K. Toth, Oak Ridge National Laboratory; C. Bingham, B. Zimmerman, J. Richards,University of Tennessee; (C.N. Davids, H. Penttilä, R. Hermann, A. Wuosmaa)

(8) High Spin Lifetime Measurement in ^{162}Yb [Yu]
C.-H. Yu, M. J. Fitch, X. H. Wang, D. Cullen, R. Gray, University of Rochester; D. Nisius, Purdue University; (I. Ahmad, B. Crowell, M. P. Carpenter, R. V. F. Janssens, R. G. Henry, T. L. Khoo, T. Lauritsen)

(9) Study of the Two-Octupole Phonon Vibrational State in ^{208}Pb [Henning]
E. F. Moore, North Carolina State University; M. Drigert, Idaho National Engineering Laboratory; S. J. Sanders, University of Kansas; D. Nisius, Purdue University; (W. F. Henning, T. L. Khoo, R. V. F. Janssens, M. P. Carpenter, T. Lauritsen, R. Henry, B. Crowell, C. J. Lister, D. Blumenthal, I. Ahmad, D. Gassman)

(10) Gamma-Ray Studies of Neutron-Rich Products of Deep-Inelastic ^{124}Sn + ^{136}Xe [Daly]
P. J. Daly, R. H. Mayer, C.-T. Zhang, D. Nisius, Z. W. Grabowski, L. Richter, Purdue University; (M. P. Carpenter, I. Ahmad, T. L. Khoo, T. Lauritsen, R. Henry, B. Crowell, R. V. F. Janssens, D. Gassman)

(11) Planar Defect Creation by HI Irradiation in Superconductors [Fendrich]
J. Fendrich, W. Kwok, G. Crabtree, ANL, Material Science Division

(12) Precision Spectroscopy of the $1s2s^3S_1$-$1s2p^3P_0$ Fine Structure Transition in Helium-Like Ni^{26+} [Livingston]
A. E. Livingston, K. Kukla, University of Notre Dame; S. Cheng, L. Curtis, University of Toledo; (R. Ali, H. G. Berry, R. W. Dunford, E. P. Kanter, C. Kurtz, B. J. Zabransky)

(13) Search for Shape-Coexisting Structures in ^{188,190}Pb via Fine Structure in the α-Decay of ^{192,194}Po [Huyse]
M. Huyse, N. Bijnens, H. Y. Hwang, J. Schwarzenberg, J. Wauters, P. Van Duppen, University of Leuven; B. E. Zimmerman, C. R. Bingham, J. D. Richards, W. Reviol, University of Tennessee; W. B. Walters, L. F. Conticchio, University of Maryland; P Mantica, Oak Ridge National Laboratory; (C. N. Davids, R. V. F. Janssens, M. P. Carpenter, I. Ahmad, H. Penttilä)

(14) Characterization of Potential Energy Surfaces in Neutron Deficient Radon Isotopes [Freeman]
S. J. Freeman, A. G. Smith, S. J. Warburton, University of Manchester; D. Nisius, Purdue University; J. Becker, Lawrence Livermore National Laboratory; (C. J. Lister, D. J. Blumenthal, R. V. F. Janssens, T. L. Khoo, B. Crowell, T. Lauritsen)

(15) Search for Bands Built on Different Shapes in ^{181}Hg [Ma]
W. C. Ma, Mississippi State University; A. Ramayya, D. T. Shi, J. Kormicki, B. Balabhadrapatruni, J. Hamilton, T. Brown, Vanderbilt University; S. Rab, Oak Ridge National Laboratory; (C. N. Davids, H. Penttilä, D. Blumenthal)

(16) Collective Excitations in ^{194}Po [Cizewski]
J. A. Cizewski, W. Younes, H. Q. Jin, D. McNabb, Rutgers University; (R. V. F. Janssens, R. Henry, D. Blumenthal, I. Ahmad, T. L. Khoo, T. Lauritsen)

(17) APEX – Target Tests [APEX]
S. M. Austin, E. Kashy, J. S. Winfield, J. E. Yurkon, Michigan State University; A. Perrera, F. L. H. Wolfs, University of Rochester; S. Gazes, M. Wolanski, University of Chicago; J. Greenberg, K. C. Chan, N. Kaloskamis, A. Chishti, Yale University; A. L. Hallin, M. Liu, Queens University; T. Trainor, University of Washington; J. D. Fox, E. Roa, Florida State University; T. Happ, GSI; M. Freer, University of Birmingham; C. Conner, University of Illinois, Chicago; D. Bazin, GANIL; S. J. Freedman, M. R. Maier, Lawrence Berkeley Laboratory; F. P. Calaprice, A. Young, Princeton University; (R. R. Betts, A. H. Wuosmaa, W. Kutschera, B. B. Back, J. P. Schiffer, I. Ahmad, D. J. Henderson, C. J. Lister, R. W. Dunford, M. D. Rhein, P. Wilt)

(18) Study of ^{18}F(p,α) and ^{18}F(p,γ) Reactions Using a Radioactive ^{18}F Beam [Rehm]
M. Paul, Hebrew University; J. Gehring, University of Chicago; C. L. Jiang, Institute of Atomic Energy, Beijing; N. Schmidt, Fachhochschule, Munich; (D. Blumenthal, J. Nolen, R. Pardo, K. E. Rehm, J. P. Schiffer)

(19) Search for K-Isomers in $^{174-176}$Hf [Lauritsen]
D. Nisius, Purdue University; (T. Lauritsen, T. L. Khoo, R. V. F. Janssens, B. Crowell, I. Ahmad, M. P. Carpenter)

(20) Hyperfine Quenching of the 2^3P_0 Level in $^{83}Kr^{34+}$ [Dunford]
S. Cheng, L. Curtis, University of Toledo; A. E. Livingston, University of Notre Dame; P. Mokler, GSI, Darmstadt; (R. Ali, H. G. Berry, D. S. Gemmell, E. P. Kanter, C. A. Kurtz, B. J. Zabransky, R. W. Dunford)

(21) FMA Studies of Proton-Rich Nuclei N~82 by γ-Ray and Conversion Electron Spectroscopy [Grabowski]
Z. Grabowski, D. Nisius, L. Richter, R. Mayer, C. T. Zhang, P. J. Daly, P. K. Bhattacharyya, Purdue University; (R. V. F. Janssens, C. N. Davids, I. Ahmad, T. L. Khoo, B. Crowell)

(22) Search for Isomers in Nuclides in and Near the Closed N=50 Neutron Shell [Walters]
W. B. Walters, L. Conticchio, J. Offenberg, Unversity of Maryland; B. Zimmerman, University of Tennessee; J. Batchelder, P. Joshi, Louisiana State University; J. Winger, Mississippi State University; (C. N. Davids, H. Penttilä)

(23) Search for Shape Isomers in ^{233}Th [Khoo]
D. Nisius, Purdue University; (T. L. Khoo, T. Lauritsen, R. V. F. Janssens, B. Crowell, I. Ahmad, M. P. Carpenter, B. B. Back, D. Blumenthal, D. Gassman)

(24) Test of the FMA Moving Tape Collector [Davids]
W. B. Walters, L. Conticchio, University of Maryland; T. Brown, Vanderbilt University; J. Batchelder, Louisiana State University (C. N. Davids, H. Penttilä, D. Henderson, R. Hermann)

(25) Radiative Capture via Inverse Kinematics [Davids]
M. Gai, J. McDonald, E. Wilds, University of Connecticut; M. Wiescher, J. Goerres, A. Garcia, University of Notre Dame; P. Woods, Edinburgh University; L. Conticchio, University of Maryland; T. Brown, Vanderbilt University; (C. N. Davids, H. T. Penttilä, D. J. Henderson, D. J. Blumenthal)

(26) Lifetime Measurements of High Spin Levels in the N=106 Nuclei ^{182}Os and ^{183}Ir [Kaczarowski]
R. Kaczarowski, SINS, Swierk; U. Garg, J. C. Walpe, B. Prause, G. Smith, R. Lehmkuhl, S. Vouzoukas, University of Notre Dame; D. Nisius, Purdue University; (R. V. F. Janssens, M. P. Carpenter)

(27) High-K Isomers in ^{176}W [Chowdhury/Crowell]
P. Chowdhury, Wellesley College; D. Nisius, Purdue University; (B. F. Crowell, D. J. Blumenthal, C. J. Lister, R. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, M. P. Carpenter, D. Gassman)

(28) Transfer Reactions with ^{92}Mo + ^{58,64}Ni [Rehm]
C. L. Jiang, Institute of Atomic Energy, Beijing; J. Gehring, University of Chicago; N. Schmidt, Fachhochschule, Munich; (K. E. Rehm, B. G. Glagola, A. Wuosmaa)

(29) Study of Wear Analysis with ^{18}F [Nolen]
C. L. Jiang, Institute of Atomic Energy, Beijing; N. Schmidt, Fachhochschule, Munich; M. Portillo, University of Texas, El Paso; (J. A. Nolen, K. E. Rehm, B. G. Glagola, J. P. Greene)

(30) ^{68}Se and the Use of the FMA for Highly Inverse Reactions [Lister]
R. Cunningham, D. Warner, Daresbury Laboratory; W. Gelletly, University of Surrey; (C. J. Lister, C. N. Davids, D. J. Blumenthal, B. F. Crowell)

(31) Deep Inelastic Scattering Near the Coulomb Barrier [Gehring]
J. Gehring, M. Wolanski, University of Chicago; C. L. Jiang, Institute of Atomic Energy, Beijing; K. C. Chan, Yale University; (K. E. Rehm, A. Wuosmaa, J. P. Schiffer, B. B. Back, D. J. Henderson)

(32) Dynamical Effects in Fusion-Like Reactions and Variation of the Nuclear Level Density with Excitation [Sarantites]
D. Sarantites, L. Sobotka, R. Charity, M. Korolija, P. Hua, Washington University; R. Fox, Michigan State University

(33) FMA Gated In-Beam Conversion Electron Measurement [Ma]
W. C. Ma, Mississippi State University; E. F. Zganjar, Louisiana State University; A. V. Ramayya, K. Bindra, T. Brown, T. Ginter, Vanderbilt University; (C. N. Davids, R. V. F. Janssens)

(34) Ion Irradiations of Layered Superconductors – Model Systems [Hettinger]
J. D. Hettinger, B. Washburn, D. J. Miller, D. Steel, ANL, Material Science Division

(35) A Search for Proton Radioactivity from $^{170,171}Au$ [Davids]
P. Woods, R. Page, Edinburgh University; M. Freer, University of Birmingham; B. Zimmerman, C. Bingham, University of Tennessee; L. Conticchio, University of Maryland; (C. N. Davids, H. Penttila, D. Blumenthal)

(36) Spectroscopy of ^{48}Cr Fission Fragments using the $^{20}Ne + ^{28}Si$ Reaction [Sanders]
S. J. Sanders, F. W. Prosser, K. A. Farrar, A. K. Dummer, University of Kansas; C. Beck, R. M. Freeman, CRN, Strasbourg; S. Cavallero, University of Catania; A. Szanto de Toledo, University of Sao Paulo; (B. B. Back, R. R. Betts, D. J. Henderson, R. V. F. Janssens, T. L. Khoo, A. H. Wuosmaa)

(37) Fine Structure in the α-Decay of ^{204}Ra [Freeman]
S. J. Freeman, J. L. Durell, A. G. Smith, S. J. Warburton, M. J. Leddy, University of Manchester; (C. N. Davids, C. J. Lister, D. J. Blumenthal, H. T. Penttilä)

(38) Heavy Ion Irradiation of High Temperature Superconductor Single Crystals [Fendrich]
J. Fendrich, W. Kwok; ANL, Materials Science Division

(39) Study of the Fusion Reactions between "Stiff" and "Soft" Nuclei [Rehm]
C. L. Jiang, Institute of Atomic Energy, Beijing; J. Gehring, University of Chicago; N. Schmidt, Fachhochschule, Munich; (K. E. Rehm, B. F. Crowell, B. G. Glagola, M. Rhein, A. H. Wuosmaa)

(40) Mass and Decay of the N=Z Nuclide ^{68}Se [Davids]
W. B. Walters, L. Conticchio, D. Mustillo, J. Swider, University of Maryland; D. Brenner, Clark University; T. Brown, Vanderbilt University; (C. N. Davids, C. J. Lister, D. J. Blumenthal, B. C. Busse)

(41) Precision Lifetime Measurement of He-Like Kr (2^3P_2) [Dunford]
S. Cheng, University of Toledo; (R. W. Dunford, R. Ali, H. G. Berry, K. E. Rehm, D. S. Gemmell, E. P. Kanter)

(42) Evaporation Residue Cross Section for the $^{100}Mo + ^{116}Cd$ Reaction [Back]
A. Caraley, D. Hofman, SUNY, Stony Brook; (B. B. Back, D. J. Blumenthal, C. N. Davids, H. T. Penttilä, A. H. Wuosmaa)

(43) Measurement of Residue Cross Sections for $^{58}Ni + ^{112}Sn$ at Beam Energies from 280 to 600 MeV [McGrath]
R. L. McGrath, A. Caraley, J. Velkovska, M. Sharan, D. Hofman, SUNY, Stony Brook; P. Decowski, Smith College; D. Magestro, Marquette University; (B. B. Back, D. J. Blumenthal, C. N. Davids)

(44) Study of the β-Delayed Proton Emission of ^{69}Kr [Batchelder]
J. Batchelder, P. Joshi, Louisiana State University; B. Zimmerman, C. Bingham, University of Tennessee; T. Brown, Vanderbilt University; E. Zganjar, Mississippi State University; K. Toth, Oak Ridge National Laboratory; W. B. Walters, University of Maryland; (C. N. Davids, H. T. Penttilä, B. C. Busse)

(45) APEX – Positron Production in Heavy Ion Collisions [APEX]
S. M. Austin, E. Kashy, J. S. Winfield, J. E. Yurkon, Michigan State University; A. Perrera, F. L. H. Wolfs, University of Rochester; S. Gazes, M. Wolanski, University of Chicago; J. Greenberg, K. C. Chan, N. Kaloskamis, A. Chishti, Yale University; A. L. Hallin, M. Liu, Queens University; T. Trainor, University of Washington; J. D. Fox, E. Roa, Florida State University; T. Happ, GSI; M. Freer, University of Birmingham; C. Conner, University of Illinois, Chicago; D. Bazin, GANIL; S. J. Freedman, M. R. Maier, Lawrence Berkeley Laboratory; F. P. Calaprice, A. Young, Princeton University; (R. R. Betts, A. H. Wuosmaa, W. Kutschera, B. B. Back, J. P. Schiffer, I. Ahmad, D. J. Henderson, C. J. Lister, R. W. Dunford, M. D. Rhein, P. Wilt)

(46) Proposal to Study New Highly Excited States in Actinide Nuclei [Lister]
S. M. Austin, E. Kashy, J. S. Winfield, J. E. Yurkon, Michigan State University; A. Perrera, F. L. H. Wolfs, University of Rochester; S. Gazes, M. Wolanski, University of Chicago; J. Greenberg, K. C. Chan, N. Kaloskamis, A. Chishti, Yale University; A. L. Hallin, M. Liu, Queens University; T. Trainor, University of Washington; J. D. Fox, E. Roa, Florida State University; T. Happ, GSI; M. Freer, University of Birmingham; C. Conner, University of Illinois, Chicago; D. Bazin, GANIL; S. J. Freedman, M. R. Maier, Lawrence Berkeley Laboratory; F. P. Calaprice, A. Young, Princeton University; U. Garg, A. Aprahamian, University of Notre Dame; E. F. Moore, North Carolina State University; (R. R. Betts, A. H. Wuosmaa, W. Kutschera, B. B. Back, J. P. Schiffer, I. Ahmad, D. J. Henderson, C. J. Lister, R. W. Dunford, M. D. Rhein, P. Wilt, R. V. F. Janssens, M. P. Carpenter, B. F. Crowell)

b. Outside Users of ATLAS and of ATLAS Technology During the Period October 1, 1993 - September 30, 1994

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
- * A. Dummer
- * K. Farrar
- F. Prosser
- S. Sanders

(2) University of Notre Dame
- A. Aprahamian
- A. Garcia
- U. Garg
- J. Goerres
- * K. Kukla
- * R. Lehmkuhl
- A. E. Livingston
- * S. Naguleswaran
- * B. Prause
- G. Smith
- * S. Vouzoukas
- * J. Walpe
- M. Wiescher

(3) Purdue University
- * P. Bhattacharyya
- P. Daly
- B. Fornal
- Z. Grabowski
- * R. Mayer
- * D. Nisius
- * L. Richter
- C. Zhang

(4) Washington University
- R. Charity
- P. Hua
- M. Korolija
- D. Sarantites
- L. Sobotka

(5) Idaho National Engineering Lab
- M. Drigert

(6) Vanderbilt University
- B. Balabhadrapatruni
- * K. Bindra
- * T. Brown
- * T. Ginter
- J. Hamilton
- J. Kormicki
- A. Ramayya
- * D. Shi

(7) Rutgers University
- J. Cizewski
- * H. Jin
- N. Koller
- * D. McNabb
- M. Satteson
- * W. Younes

(8) Lawrence Livermore National Lab
- J. Becker

(9) University of Rochester
- D. Cullen
- * M. Fitch
- * R. Gray
- * A. Perrera
- * X. Wang
- F. Wolfs
- C.-H. Yu

(10) University of Connecticut
- M. Gai
- * J. McDonald
- E. Wilds

(11) University of Chicago
- S. Gazes
- * J. Gehring
- * M. Wolanski

(12) University of Catania
- S. Cavallero

(13) University of Toledo
- S. Cheng
- L. Curtis

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

(15) Fachhochschule, Munich
- N. Schmidt

(16) Louisiana State University
J. Batchelder
* P. Joshi
E. Zganjar

(17) Institute of Atomic Energy, Beijing
C. Jiang

(18) CRN, Strasbourg
C. Beck
R. Freeman

(19) Australian National University
A. Baxter
A. Byrne
G. Dracoulis

(20) University of Maryland
* L. Conticcio
* D. Mustillo
* J. Offenberg
* J. Swider
W. Walters

(21) Yale University
* K. Chan
A. Chishti
J. Greenberg
* N. Kaloskamis

(22) Materials Science Division, ANL
G. Crabtree
J. Fendrich
K. Gray
J. Hettinger
W. Kwok
D. Miller
D. Steel
* B. Washburn

(23) Hebrew University
M. Paul

(24) University of Tennessee
C. Bingham
* W. Mueller
W. Reviol
* J. Richards
B. Zimmerman

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

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

(27) Michigan State University
S. Austin
R. Fox
E. Kashy
J. Winfield
J. Yurkon

(28) Princeton University
F. Calaprice
A. Young

(29) Daresbury Laboratory
R. Cunningham
D. Warner

(30) Mississippi State University
W.-C. Ma
J. Winger

(31) Oak Ridge National Laboratory
S. Rab
K. Toth

(32) Wellesley College
P. Chowdhury

(33) Lawrence Berkeley Laboratory
S. Freedman
M. Maier

(34) University of Birmingham
M. Freer

(35) University of Leuven
* N. Bijnens
M. Huyse
P. VanDuppen
J. Wauters

(36) GSI, Darmstadt
T. Happ
P. Mokler

(37) Queens University, Ontario
A. Hallin
* M. Liu

(38) Edinburgh University
R. Page
P. Woods

(39) University of Illinois, Chicago
* C. Conner

(40) GANIL
D. Bazin

(41) North Carolina State University
E. F. Moore

(42) University of Manchester
J. Durell
S. Freeman
M. Leddy
W. Phillips
A. Smith
* S. Warburton

(43) University of Washington
T. Trainor

(44) University of Surrey
W. Gelletly

(45) SINS, Swierk
R. Kaczarowski

(46) Clark University
D. Brenner

(47) SUNY, Stony Brook
* A. Caraley
* D. Hofman
R. McGrath
M. Sharan
* J. Velkovska

(48) University of Texas, El Paso
* M. Portillo

(49) Smith College
P. Decowski

(50) Marquette University
D. Magestro

c. Summaries of the Continuing User Programs for FY1994

c.a. The University of Notre Dame

c.a.1. Nuclear Physics (U. Garg, W. Reviol (University of Tennessee), R. Kaczarowski (SINS, Swierk), 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 A=180 (i.e. the Hg-Pt-Os nuclei), and A=100 (i.e. the Ru-Tc nuclei) with emphasis on shape coexistence and configuration mixing. This group has also participated in many other experiments performed with the BGO gamma-ray facility, especially in the investigation of superdeformation. The γ-ray groups at ANL and Notre Dame have also had collaborative experiments at Gammasphere. The Notre Dame group has built, tested and extensively used a state-of-the-art plunger device for lifetime measurements in conjunction with the ATLAS γ-ray facility. An adapted version of this device is now under construction at Notre Dame, under contract with ANL, for use at the Gammasphere facility.

c.a.2. Atomic Physics (A. E. Livingston, K. Kukla, S. Cheng (University of Toledo), L. Curtis (University of Toledo))

In a collaboration with the Atomic Physics group at Argonne and the University of Toledo, the Atomic Physics group at the University of Notre Dame is measuring the fine structure transition energies in highly-charged lithium-like and helium-like ions using beam-foil spectroscopy. Precise measurements of 2s-2p transition energies in simple (few-electron) atomic systems provide stringent tests of several classes of current atomic-structure calculations. Analyses of measurements in helium-like Ar^{16+} have been completed, and the results submitted for publication. A current goal is to measure the $1s2s^3S_1$ - $1s2p^3P_0$ transition wavelength in helium-like Ni^{26+}. Measurements of the $1s2s^2S_{1/2}$ - $1s2p^2P_{1/2,3/2}$ transition wavelengths in lithium-like Kr^{33+} is planned. Wavelength and lifetime measurements in copper-like U^{63+} are also expected to be initiated. The group is also participating in measurements of forbidden transitions in helium-like ions. A measurement of the lifetime of the $1s2s^3S_1$ state in Kr^{34+} was published recently. In a collaboration including P. Mokler of GSI, Darmstadt, measurements have been made of the spectral distribution of the 2E1 decay continuum in helium-like Kr^{34+}. Initial results have been reported and further measurements are planned.

c.b. Purdue University (P. Daly, Z. Grabowski, R. H. Mayer, D. Nisius, L. Richter, P. Bhattacharyya, C. T. Zhang)

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 is studying proton-rich nuclei with N~82 using the FMA and an electron spectrometer. Furthermore, D. Nisius 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, A. Dummer, and K. Farrar)

This past year the Kansas group achieved its objective of studying the fusion-fission mechanism for three different entrance channels populating ^{48}Cr with the measurement of the $^{20}Ne+^{28}Si$ reaction. Previously the group had studied the $^{24}Mg+^{24}Mg$ reaction in a particle-only measurement and the $^{36}Ar+^{12}C$ reaction in a particle-gamma coincidence measurement. The latest experiment was done at the ATLAS gamma-ray facility and employed a particle-particle-gamma coincidence arrangement. The $^{20}Ne+^{28}Si$ data seem to confirm the picture that has been emerging of a population of states in the fission fragments that is largely determined by a statistical phase space. Significant discrepancies in the observed and predicted population for some excitations, however, suggest that either a different reaction mechanism may be involved in these populations, or a different spin distribution of the compound nucleus is present than is assumed for the calculations. The group is now working with the data for all three reactions in an attempt to develop an overall consistent picture.

In a separate program the group has been analyzing data from a $^{136}Xe+^{64}Ni$ particle-gamma coincidence measurement that was done during the summer of 1993 at ATLAS. This latter measurement was motivated as an attempt to find evidence for low-spin shape-isomerism in the ^{66}Ni nucleus. Although no clear signature for such behavior was observed, the data are still useful in helping to characterize the production cross sections, angular distributions and spin populations in the $^{136}Xe+^{64}Ni$ reaction. The group is also participating in the ongoing search at ATLAS for evidence of a double-phonon, octupole-vibration excitation in ^{208}Pb.

Group member Kelly Farrar was awarded his doctorate degree last year for his research involving the $^{36}Ar+^{12}C$ system.

c.d. <u>**Vanderbilt University**</u> (A.V. Ramayya, J. H. Hamilton, K. Bindra, J. Kormicki, B. R. S. Balabhadrapatruni, D. T. Shi, L. T. Brown, and W.-C. Ma [Mississippi State University])

An experiment identifying gamma-ray transitions in ^{183}Hg using γ–γ and recoil-γ coincidences has been performed at the FMA and published. Five bands were observed, of which two are associated with the [624]9/2$^+$ orbital and exhibit signature splitting. Two other bands which do not show signature splitting have been associated with the [514]7/2$^-$ orbital and exhibit transition energies almost identical to bands with the same configuration in ^{185}Hg. New experiments on identification of bands in ^{181}Hg and an in-beam study of conversion electrons from ^{183}Hg have been performed in 1994. Three bands were identified for the first time in ^{181}Hg. A mini-orange electron spectrometer was used in a test run where background were investigated. One member of the collaboration, K. Bindra, who is a Ph.D. student, and a new student, L. Brown, have been working full-time under the direction of Cary Davids. K. Bindra has now graduated.

c.e. <u>**Idaho National Engineering Laboratory**</u> (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. Among the present tasks under way are the migration of the analysis software to UNIX platforms and the expansion of the software's graphics capabilities. M. W. Drigert has been heavily involved in the superdeformation studies in the Dy and Pb mass regions. He has also been interested in the study of octupole stability in the light actinide mass region. Future research plans include further studies of nuclei in the light actinide region, with the emphasis on using the FMA in conjunction with the Ge detectors from the γ-ray facility to investigate nuclei which can only be populated by charged particle evaporation channels.

c.f. <u>**University of Tennessee, University of Maryland, and Oak Ridge National Laboratory**</u> (C. R. Bingham, J. D. Richards, B. Zimmerman, W. B. Walters, L. F. Conticchio, and K. S. Toth)

This collaboration has been involved in the study of alpha-decaying nuclei in the A > 180 region using the double-sided silicon strip detector implantation facility at the FMA. They are also active participants in the proton radioactivity experiments (see Sec. I.C.1). An experiment on high-spin isomers in the neutron-deficient Cd region is planned for the near future.

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 fabricated the niobium resonators and some auxiliary devices for the superconducting-linac energy booster built at Florida State University. Personnel from FSU came 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. Carnes, and V. Needham)

Argonne has fabricated the niobium resonators and some other linac components required for the superconducting accel/decel linac now in operation 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 return occasionally to assemble and test the resonators. There is a continuing interchange of technical information between ANL and KSU related to linac operations, tuning, and resonator maintenance.

d.c. University of Sao Paulo (J. C. Acquadro, N. Added, M. Ferraretto, J. Ordonez, 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 returned to ANL in 1993 for assembly and testing of the first batch of completed resonators. The fabrication of the resonators will be completed by early 1995 when the Sao Paulo personnel will come back for final assembly and testing. Fabrication of electronics modules at ANL is still in progress.

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 tests on the niobium prototype are currently in progress. Some technical details of this project are described in the Superconducting Linac Development section of this report. All funding for the prototype has come from the NSC, and they have also stationed two staff members at ATLAS for the past two years to gain experience and work on this project. Additional NSC personnel visited ATLAS for extended periods during 1994 for electronics and cryogenics experience and training. Two NSC staff members are scheduled to spend several months at ANL during 1995 to continue tests and developments of the prototype resonators and to initiate fabrication of the production models for their linac project.

II. OPERATION AND DEVELOPMENT OF ATLAS

These sections report on the operation and development of the Argonne Tandem 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 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. The new charge-state selector, funded as an Accelerator Improvement Project, is now in routine use at ATLAS. This simplifies and improves reliability of operations for beams such as uranium that require stripping to reach Coulomb-barrier energies. Figure II-1 shows the usage of various beams for research at ATLAS during FY 1994.

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.

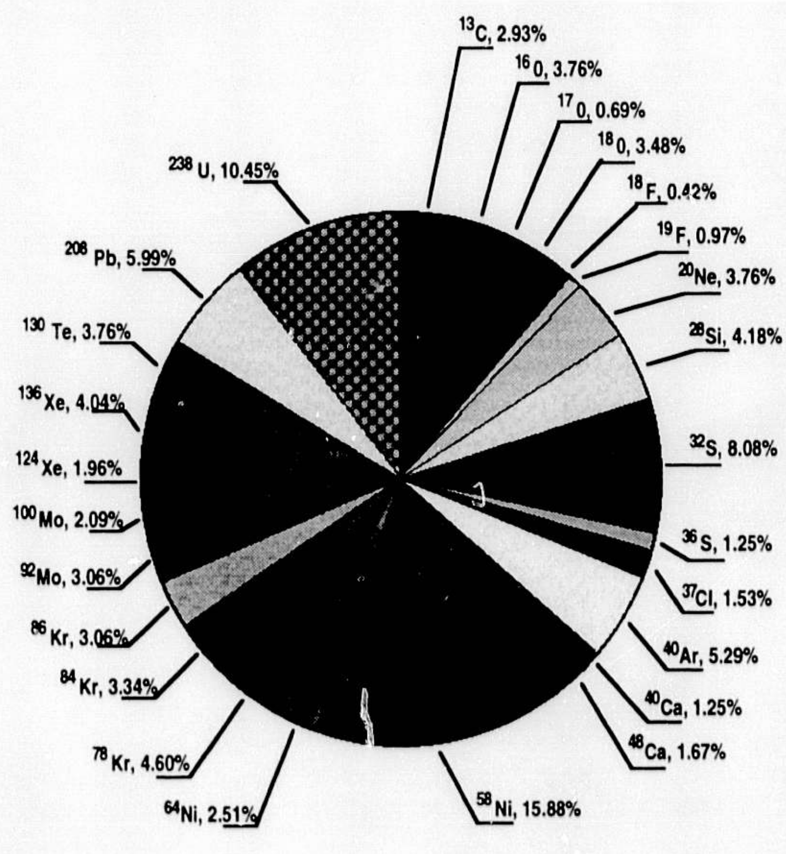

Figure II-1. "PII" chart of the beams used in research at ATLAS during FY 1994.

In addition, accelerator issues related to radioactive beams are currently being investigated. Progress reports on the work are presented in subsection D below. Figure II-2 is a group photo of the ATLAS accelerator operations and development staff taken in December 1994.

Figure II-2. ATLAS Operations and Development Staff

Currently, the facility is on a seven-day week operating schedule. An increase in funding as part of the DOE Scientific Facilities Initiative was requested, beginning in FY 1996, to bring the staff level and operations budget up to that required for steady-state seven-day operation. The requested budget will permit the delivery of 5600 hours per year of beam on target for research. This will significantly enhance our ability to serve the increased level of demand for beam time from the ATLAS user community.

Several other upgrades are currently in progress at ATLAS. An upgrade of the 3 ATLAS liquid helium refrigerators to reduce electrical power usage was funded by the DOE in-house energy management program, and is scheduled to be completed by summer 1995. A second, and more advanced Electron Cyclotron Resonance (ECR) ion source system, funded as an Accelerator Improvement Project, is under construction, and scheduled for completion in FY 1996. Improved beam monitoring will be possible with a new type of non-intercepting beam intensity and phase pickup system. A prototype is working well at the entrance of the PII linac, and more units will be installed during FY 1996.

	FY 1994 (actual)	FY 1995 (extrap.)	FY 1996 (pred.)	FY 1997 (pred.)
Beam Use for Research (hr)				
Nuclear Physics	4870	4500	5250	5250
Atomic Physics	288	250	290	290
Other	40	50	60	60
Total	5198	4800*	5600	5600
Number of Nuclear Experiments Receiving Beam	60	55	70	70
Number of Scientists Participating in Research	153	150	180	180
Institutions Represented				
Universities (U.S.A.)	27	29	33	33
DOE National Laboratories	5	5	5	5
Other	18	15	20	20
Usage of Beam Time (%)				
In-House Staff	37	37	35	35
Universities (U.S.A.)	49	49	51	51
Other DOE National Laboratories	2	2	2	2
Other Institutions	12	12	12	12
Total	100	100	100	100

*Reduced beam time in FY 1995 due to two-month shutdown for cryogenic efficiency upgrade.

A. OPERATION OF THE ACCELERATOR

R. C. Pardo, B. Batzka, P. J. Billquist, J. Bogaty, B. E. Clifft, S. L. Craig, R. E. Harden, R. Harkewicz, D. Herbst, S. Kramer, B. Millar, F. H. Munson, Jr., K. Nakagawa, D. R. Phillips, C. Roehrig, A. Ruthenberg, J. R. Specht, P. Strickhorn, A. Sutherland, B. Tieman, I. R. Tillbrook, R. Vondrasek, and G. P. Zinkann

Fiscal Year 1994 was the first year of seven-day operation since ATLAS became a national user facility in 1985. ATLAS made the most of the opportunity this year by providing 5200 hours of beam on-target to the research program. A record number of 60 experiments were completed and the "facility reliability" remained near the 90% level.

Seven-day operation was made possible with the addition to the staff of two operator positions providing single-operator coverage during the weekend period. The normally scheduled coverage was augmented by an on-call list of system experts who respond to emergencies with phone-in advice and return to the Laboratory when necessary. This staffing approach continues but we rearranged our staffing patterns so that we now have one cryogenics engineer working a shift pattern which includes 8-hour daily coverage during the weekend.

ATLAS provided a beam mix to users consisting of 26 different isotopic species, 23% of which were for A≥100 in FY 1994. Approximately 60% of the beam time was provided by the Positive Ion Injector, slightly less than the usage rate of FY 1993. Experiments using uranium or lead beams accounted for 16.4% of the total beam time. The ECR ion source and high-voltage platform functioned well throughout the year. A new technique for solid material production in the source was developed which uses a sputtering process wherein the sample of material placed near the plasma chamber wall is biased negatively. Plasma ions are accelerated into the sample and material is sputtered from the surface into the plasma. This technique is now used routinely for many elements. Runs of calcium, germanium, nickel, lead, tellurium, and uranium were carried out with this technique.

A new charge-state selector was installed at the exit of the PII linac and became operational in August 1994. A photograph of the installed device is shown in Figure II-3. It was used in five uranium and

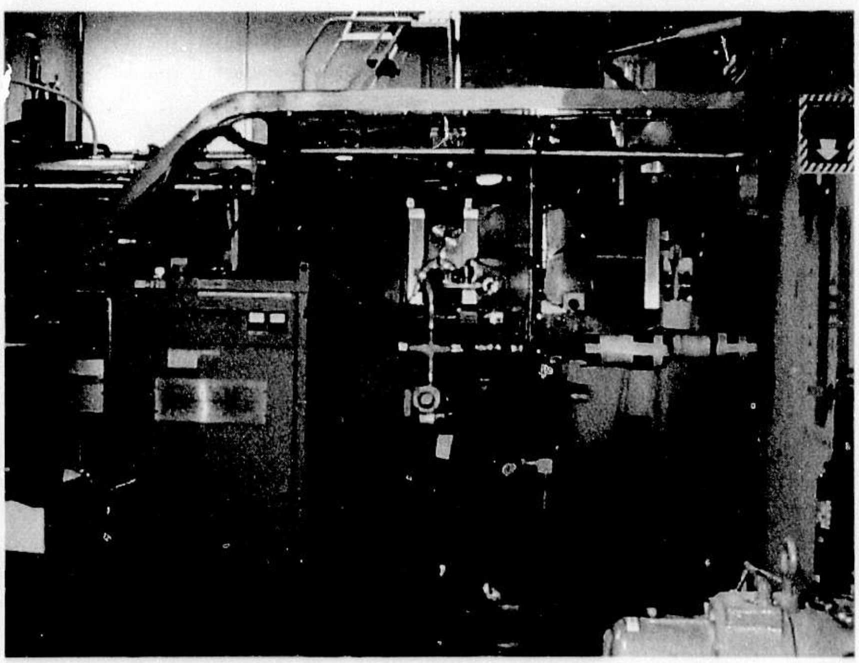

Fig. II-3. The charge-state selector.

lead runs that require stripping before acceleration in the main linac. The system worked well in the initial runs. The selector eliminates the need for the elaborate and time-consuming "guide-beam" setup for the booster linac section and speeds the setup time for heavy, stripped beams considerably. The use of the charge-state selector also solved the problem of beam current limitations due to the quenching of solenoids in the booster linac due to heating from the untuned charge-state ions hitting the focussing solenoids. About 20% transmission loss is experienced because of the different optics required in the transport region to the booster linac. This is a difficult beam optics region for us since the total vertical gap of the tandem analyzing magnet, which the PII beams must traverse, is only one centimeter.

The facility had no extended downtimes for maintenance during FY 1994 even though the new charge-state selector was installed and commissioned during the year. The tandem was down for two months while the voltage-distributing corona system was rebuilt. These activities were carried out in parallel with the ongoing research program by scheduling tandem injector runs during the charge-state selector installation and PII runs during the tandem maintenance period.

The maintenance work on the tandem corona system was accomplished during a two-month period. The corona needles are enclosed in separate tube sections which allows dynamic control of the corona currents by control of the gas pressure. These units, which operated unattended for a decade, were removed and sent to National Electrostatics Corporation for refurbishment. Additional maintenance work was performed on the Pelletron charging system resulting in significantly improved terminal charging currents. The entire repair went smoothly and the tandem has returned to operation. Terminal voltage stability is much improved and we are now able to operate at our historical standard of 8.5-MV terminal potential.

The facility continued to be plagued with unreliable primary power delivery from the Laboratory's power grid. Two significant power outages occurred in FY 1994 in addition to one experienced in May 1993. The root cause of the outages differed in each case but are related to an old primary power distribution system in the Laboratory which supplies power to the entire building. The Laboratory has initiated a project to replace the primary power distribution system in the 200 area of the Laboratory and that project is expected to be completed in the summer of 1995.

The lack of an automatic switch on one of the substations supplying power to ATLAS was also highlighted in two of the more recent outages. Over the 1994 Christmas holiday period that manual switch was replaced with an automatic switch. This new configuration will restore power to the affected areas of ATLAS within one or two seconds after loss of primary power by switching to the secondary power leg. The cryogenics group is installing uninterruptible power sources to carry the cryogenic system through such short (few seconds) power outages. These upgrades, when complete, should provide ATLAS with a much improved ability to handle brief power bumps.

The ATLAS cryogenic system functioned quite reliably this year. The new wet engine installed in October 1993 and reported in last year's FWP provided added capacity which improved our ability to run the heaviest beams such as uranium in a much more reliable manner. ATLAS will begin a two-month down period in April 1995 to install the remaining two wet engines which will further enhance the system capacity and efficiency.

B. RECENT AND PLANNED IMPROVEMENTS AT ATLAS

a. <u>Charge-State Selector Installed</u> (S. L. Craig, J. A. Nolen, D. Phillips, D. Herbst, G. Zinkann, P. Strickhorn, F. Munson, C. Roehrig, S. Kramer)

The installation and early operation of the new charge-state selector after the PII linac was described above. Previous to the use of this device all charge states of beams stripped between the PII and Booster linacs entered the Booster. The beam power of the unused charge states often caused quenching of superconducting solenoids in the Booster. This problem is completely eliminated by the charge-state selector. It also eliminates the need to use "guide beams" from the tandem when tuning heavy beams which required stripping.

b. <u>Upgrade of the Linac Control System</u> (F. Munson, B. Tieman, S. Kramer)

The new ATLAS control system, based on the commercial product "VISTA", continues to be developed and to absorb more of the facility control work load. Cryogenic temperature is now monitored by the new system and the old temperature monitoring system was retired. Resonator and solenoid control can now be handled by the new system. With this step, all components of the accelerator can now be operated from the new system. Many of the "high-level" programs remain to be ported to the new system, but we believe that all features available from the old system will be available on the new system by October 1995.

The enhanced features of the new system, distributed control, and user-friendly interfaces make the new system the one of choice. So as new capabilities are made available, they are quickly adopted as the system-of-choice by the operators.

c. <u>Beam-Phase Monitoring with Non-Destructive Pickup</u> (J. Bogaty, B. E. Clifft)

An intensity and phase-sensitive capacitive pickup was installed at the entrance to the PII linac. This device is based on an extension of the design of the Beam Current Monitor developed as part of the ATLAS radiation safety system. The purpose of the pickup is to allow the arrival phase of the beam from the ECR source at the entrance to the PII linac to be set to a standard which reproduces previous tune conditions and establishes a standard. The new pickups and associated electronics demonstrated sensitivity well below 1 electrical nanoamp but can handle beam currents of many electrical microamps as well. In addition to phase information, beam current is also measured by the units thus providing a continuous, non-intercepting current readout as well.

From the very first use of PII, we established a few "reference tunes" for the linac and scaled those tunes for any other beam desired. For such scaling to work properly, the velocity and phase of the beam from the ion source must be fixed and reproducible. In last year's FWP the new ATLAS Master Oscillator System was described. The new system has the ability of easily adjusting the beam arrival phase at the entrance to each of the major sections of the facility — PII, Booster, ATLAS. Our present techniques for establishing the beam arrival phase at the entrance of each of the linac sections are cumbersome and, sometimes, intellectually challenging. The installation of these capacitative pickups at the entrance to each of the linac sections will make the determination and setting of the beam arrival phase direct, simple, and dynamic. This should dramatically shorten our setup time for "old-tune" configurations and increase useful operating hours.

Permanent electronics for the PII entrance pickup is under construction. During the remainder of this year we expect to implement similar units at the Booster and ATLAS linac section entrances and at selected locations in the experimental areas, such as the FMA.

d. Beam Tuning (R. C. Pardo and G. P. Zinkann)

A program for configuring the linac, based on previously run configurations for any desired beam was used during the past year. This program uses only a small number of empirical tunes to scale resonator fields to properly accelerate a beam with a different charge-to-mass (q/A) ratio from the original tune configuration. The program worked very well for the PII linac section where we can easily match a new beam's arrival phase and velocity to the tuned value. It was also fairly successful for the Booster and ATLAS sections of the linac, but not as successful as for the PII linac. Most of the problems are associated with setting the beam arrival time correctly for each major linac section. This problem is being addressed with the development of the capacitive pickup beam phase monitor discussed above. During the next year we expect to improve our ability to quickly configure the linac for new beams and reduce the time required for linac tuning. Already the time required for linac tuning as a percentage of research hours has decreased from 22% in FY 1993 to 15% in the first quarter of FY 1995.

e. Helium-Refrigeration System (J. R. Specht, B. Millar, A. Sutherland)

The design, procurement, and preliminary construction was completed for adding two more wet expansion engines to two helium refrigerators. These will be added in mid-year FY 1995. In addition a variable speed drive will be added to an existing helium compressor. This is part of an energy conservation upgrade project to reduce operating costs from the use of electricity and liquid nitrogen. This project involves the replacement of Joule-Thompson valves in the refrigerators with expansion engines resulting in system efficiency improvements of about 30% and improved system reliability. A photograph of the wet engine near the 2800 West refrigerator during the early stages of installation is shown in Figure II-4.

The implementation of uninterruptible power supplies into the helium refrigerators' control systems will also be completed this fiscal year. This will allow the refrigerators to automatically restart in the event of short-term electrical power failures. This will result in reduced accelerator down time and saving helium gas which is lost during power failures.

Other additions have improved operations. The installation of a 30,000-gallon helium storage tank, which was obtained as surplus from the ANL CWDD project, was completed. The tank allows the storage of all the liquid helium used in ATLAS by converting it to gas if necessary. It can then be reliquified later resulting in lowered operating costs. The new PLC/PC-based cryogenic alarm system will allow additional needed alarms and will be of fail-safe design. This system will be fully implemented this fiscal year.

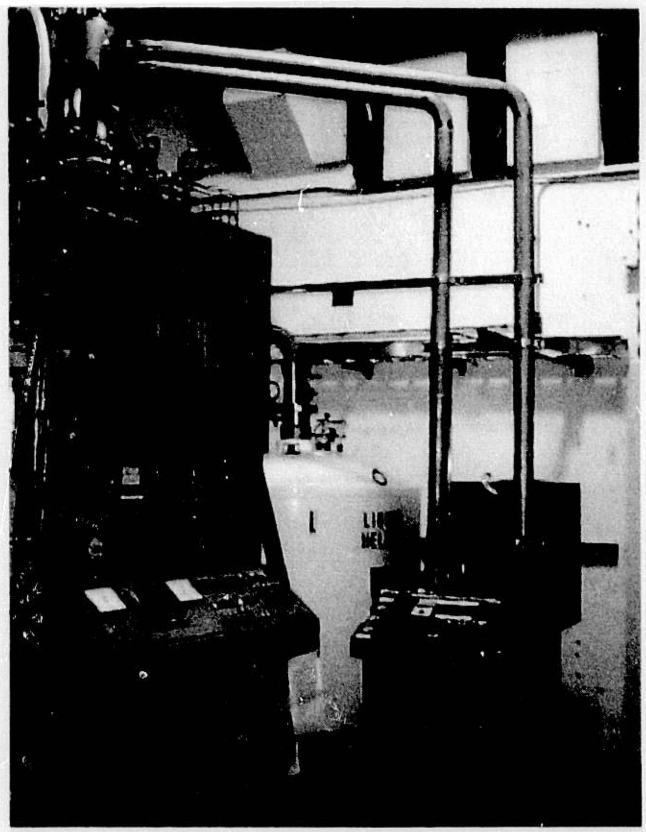

Fig. II-4. The new wet engine (right) connected to the 2800 West refrigerator (left).

C. ACCELERATOR PHYSICS AND LINAC DEVELOPMENT

J. A. Nolen, R. C. Pardo, K. W. Shepard, R. Harkewicz, J.-W. Kim, J. Bogaty, B. Clifft, G. Zinkann, M. Kedzie, T. Barlow, and K. Beyer

This section describes the accelerator-physics program that initially developed the underlying methods which made the ATLAS facility possible. This is now an ongoing 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 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 significance. 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. This development extended the useful velocity range of superconducting heavy-ion accelerating structures to a value 5 times lower than previously possible. 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, now routinely produces CW beams of lead and uranium in the 6- to 6.8-MeV-per-nucleon energy range at intensities on target of up to 5 pnA.

Other developments include the design, construction, testing, and commissioning of an advanced ECR ion source for ATLAS. This work is in collaboration with C. Lyneis and D. Xie at LBL. The layout of the addition to the building for the source and a cross section of the new source are shown in Figures II-5 and II-6.

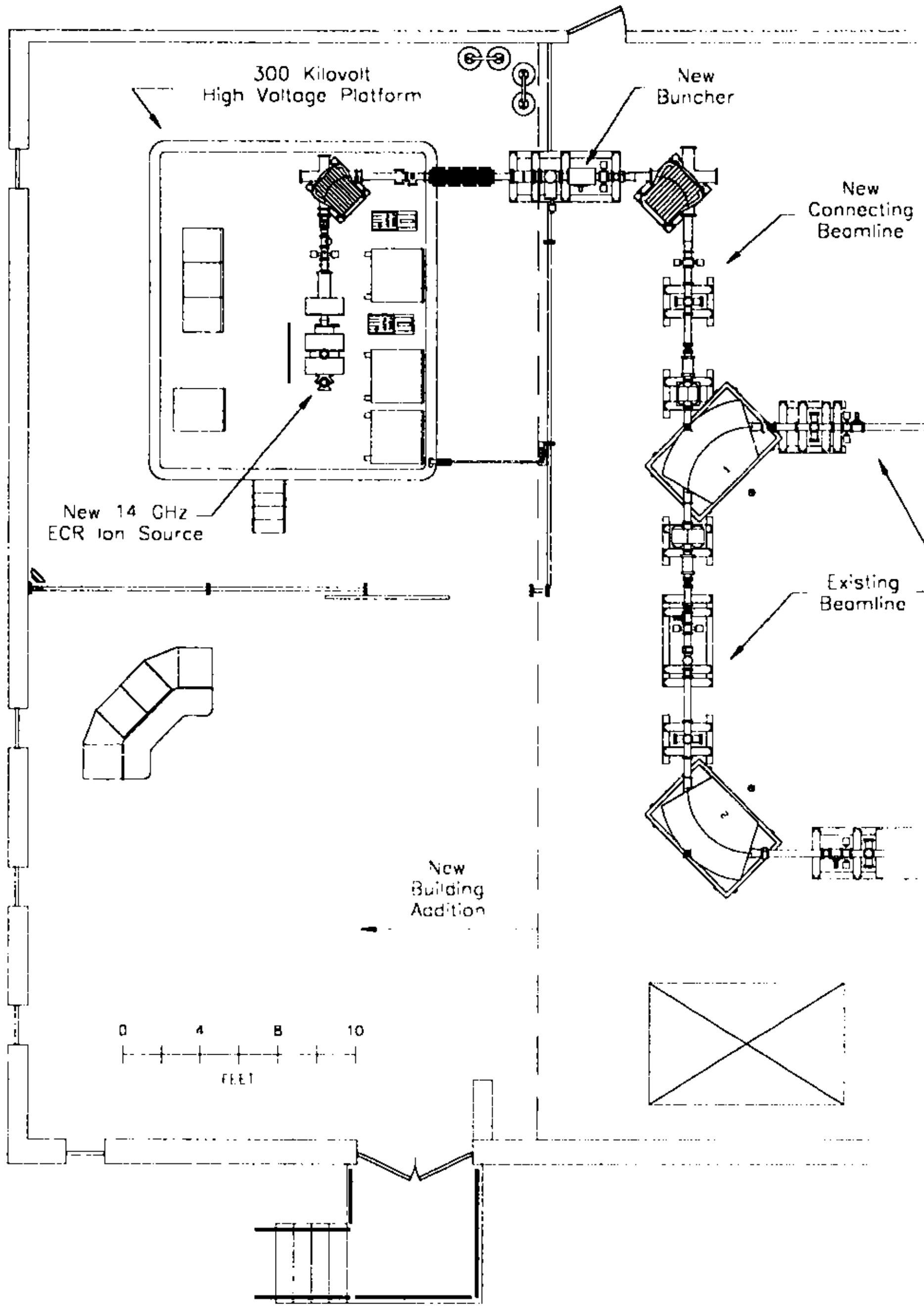

Fig. II-5 . Plan view of the new high-voltage platform, 14 GHz ECR ion source, and beam line showing their relationship to the present PII injection beam line.

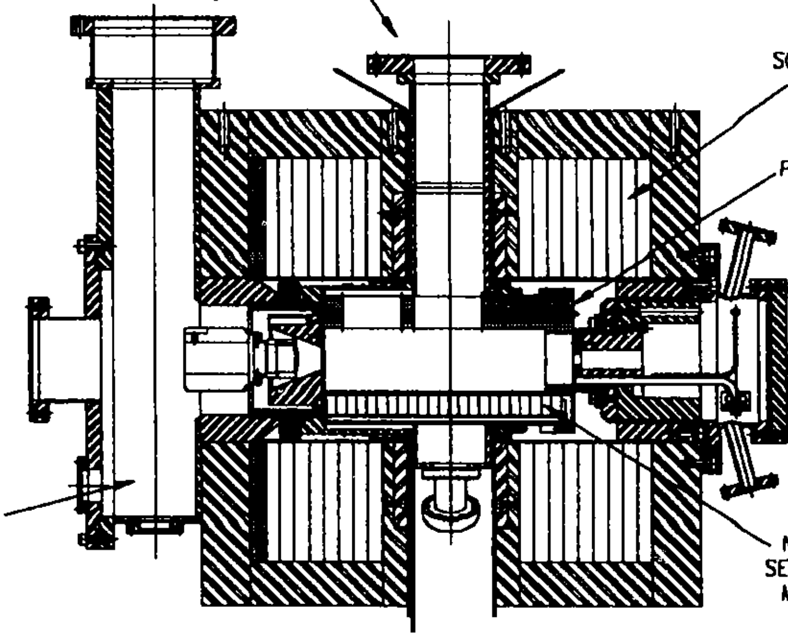

Fig. II-6. Section view of the new 14 GHz ECR ion source.

Implementation of non-intercepting beam phase and intensity monitors along the ATLAS beam lines is also in progress.

a. <u>ECR Ion Source</u> (P. J. Billquist, R. Harkewicz, R. C. Pardo)

The feasibility of using a 30-watt pulsed NdYAG laser to ablate or evaporate material directly into the ECR had some initial exploratory runs and produced two distinctly interesting results. This technique holds the possibility of using small quantities of material, with a high efficiency, and being applicable to all solids. The laser illuminates a sample through one of the radial ports in the ECR main plasma chamber. The off-line tests indicated that our surplus (free) laser is capable of ablating significant quantities of interesting materials.

The first tests of the laser ablation idea were carried out using a bismuth sample. The inherent pulsed nature of the technique allowed us to immediately study the time evolution of charge states in the ECR plasma. The results are directly comparable to model calculations and are completely consistent with the sequential stepwise stripping process which was assumed to dominate the high charge state production process. A paper describing our results will be presented at the 1995 International Ion Source Conference.

In the process of these laser studies, we decided to bias the bismuth sample to better understand some of the features of the observed ion time distribution spectra. When we applied the bias to the sample we noticed that with the sample biased negatively with respect to the plasma chamber, a beam of bismuth was observed immediately even without the laser operating. The amount of beam depended on the bias voltage. Further consideration and tests confirmed that the material from the bismuth sample was being sputtered into the plasma by plasma ions accelerated into the bismuth sample by the bias voltage. This novel and exciting technique for introducing solid materials into the ECR plasma and producing beams from those materials was developed and used for a number of actual experimental runs at ATLAS during the past year. Beams of calcium, nickel germanium, tellurium, gold, lead, and uranium were produced in this manner.

b. **Positive-Ion Injector Cryogenic Heat Load** (G. P. Zinkann, J. R. Specht, M. Kedzie, G. Wiemerslage)

A project to improve the temperature profile of the nitrogen heat shield on the PII linac cryostats began. The goal of the project is to reduce the liquid nitrogen consumption and the quiescent cryostat heat load to the helium refrigeration system. In March 1994 additional heat shield components were installed in one PII cryostat. A significant improvement in the quiescent helium system heat load of approximately 10 watts was observed and some improvement in liquid nitrogen consumption was also noted. We plan to extend these improvements to the remaining two cryostats in the next year as access time can be schedule.

c. **Beam Diagnostics** (J. Bogaty, B. E. Clifft, G. P. Zinkann, R. C. Pardo)

The ECR-PII injector beam line is operated at a fixed ion velocity. The platform high voltage is chosen so that all ions have a velocity of 0.0085c at the PII entrance. If a previous tune configuration for the linac is to be used, the beam arrival time (measured in rf phase units) must be matched to the previous tune as well. A nondestructive beam-phase pickup detector was developed and installed at the entrance to the PII linac. This device provides continuous phase and beam current information and allows quick optimization of the beam injected into PII. Bunches traverse a short tubular electrode thereby inducing displacement currents. These currents are brought outside the vacuum interface where a lumped inductance resonates electrode capacitance at one of the bunching harmonic frequencies. This configuration yields a basic sensitivity of a few hundred millivolts signal per microampere of beam current. Beam-induced radiofrequency signals are summed against an offset frequency generated by our master oscillator. The resulting kilohertz difference frequency conveys beam intensity and bunch phase information which is sent to separate processing channels. One channel utilizes a phase locked loop which stabilizes phase readings if beam is unstable. The other channel uses a linear full wave active rectifier circuit which converts kilohertz sine wave signal amplitude to a D.C. voltage representing beam current. A prototype set of electronics is now in use with the detector and we began to use the system in operation to set the arrival beam phase. A permanent version of the electronics system for the phase detector is now under construction. Additional nondestructive beam intensity and phase monitors at the "Booster" and "ATLAS" linac sections are planned as well as on some of the high-energy beam lines. Such a monitor will be particularly useful for FMA experiments where the primary beam hits one of the electric deflector plates rather than a conventional Faraday cup.

d. **Technology of RF Superconductivity**

This work has several parts, two of which are collaborative development projects with the majority of the work being performed at Argonne. The first is the development of a superconducting RFQ structure in collaboration with AccSys Technology Inc. of Pleasanton, California, funded as a Phase II SBIR grant. Another is a collaborative project with the Nuclear Science Centre, New Delhi, India (who are funding the work) to develop new superconducting ion accelerating structures. Other initiatives are developing various aspects of the technology required to utilize ATLAS as a secondary beam linac for radioactive beams.

i. Superconducting RFQ Development

Construction of a niobium superconducting RFQ structure is near completion in the Argonne Central Shops. The work being performed is to construct and test (without beam) a superconducting RFQ device. The niobium RFQ was assembled and shimmed and tuned for final frequency and vane voltage balance. Chemical and heat treatment of the vanes is in progress and will be followed by final welding and testing. The resonant frequency of the structure is 194 MHz and the vane modulations are appropriate for velocities from 0.02 to 0.08c, at the input and output, respectively.

ii. Quarter-Wave Coaxial-Line Niobium Resonators

The 97-MHz, 15-cm active length structures are designed and three resonators are being constructed as prototypes for use in a booster linac at the Nuclear Science Centre, Delhi, India. The structure is suitable for the velocity range 0.06 to 0.15 c. The design emphasis is to improve performance and reduce costs relative to the existing ATLAS split-ring accelerating structures. The first resonator is complete and in the process of diagnostic tests and debugging. The resonator is pulsed to gradients greater than 5 MV/m. Although low-level multipacting in the structure is severe, it can be eliminated by rf conditioning and does not appear to present any operational problems. Diagnostic work is in progress to repair a region of excessive rf loss at the shorted end of the prototype structure which presently limits CW operation to 2 MV/m.

iii. Superconducting Resonator Processing Facilities

Computer control and interlock systems were installed for both the electrochemical processing facility and the 1250° C vacuum furnace. The PC-based systems provide better control and data logging, and improved interlock capabilities for these facilities which are used for development, construction, and maintenance of superconducting resonators not only for ATLAS, but for a number of other laboratories (Florida State University, Kansas State University, University of Sao Paulo, and the Nuclear Science Centre, New Delhi, India).

D. RADIOACTIVE BEAM INITIATIVES

Plans for the future include R&D on various aspects of linac technology related to the production and acceleration of radioactive beams. Of immediate interest are the development of a high-gradient superconducting quadrupole for use in a low q/m linac, a normally conducting, low-frequency RFQ for the first stage of a secondary beam accelerator, and a 24-MHz superconducting resonator for use at one half the velocity now possible with PII. Other issues include the investigation of techniques for remote handling and maintenance fo radioactive components, possibly based on sensor and visualization technology developed for "virtual reality" applications.

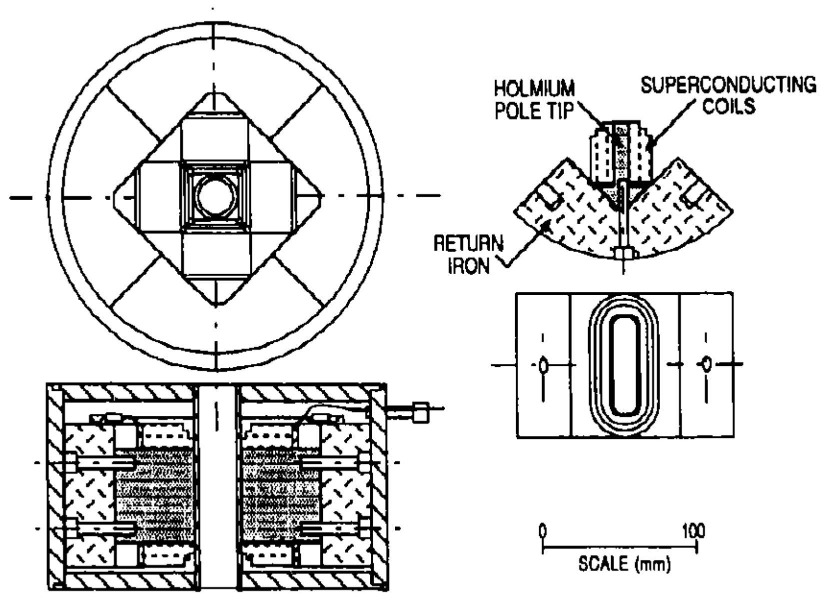

Fig. II-7. Schematic of the 350 T/m superconducting quadrupole being developed as a focussing element for use in a low q/A pre-accelerator for radioactive beams.

a. <u>Superconducting Magnetic Quadrupole</u> (J. W. Kim, K. W. Shepard) and J. A. Nolen)

A design was developed for a 350 T/m, 2.6-cm clear aperture superconducting quadrupole focussing element for use in a very low q/m superconducting linac as discussed below. The quadrupole incorporates holmium pole tips, and a rectangular-section winding using standard commercially-available Nb-Ti wire. The magnet was modeled numerically using both 2D and 3D codes, as a basis for numerical ray tracing using the quadrupole as a linac element. Components for a prototype singlet are being procured during FY 1995.

b. <u>Low-Charge-State Linac</u> (K. W. Shepard, J. W. Kim)

A design is being developed for a low-charge-state linac suitable for injecting ATLAS with a low-charge-state, radioactive beam. Initial work indicates that the existing ATLAS interdigital superconducting accelerating structures, together with the superconducting quadrupole transverse focussing element discussed above, provides a basis for a high-performance low-charge-state linac (see Figs. II-8 and II-9). The initial 2 or 3 MV of such a linac could be based on a normally-conducting, low-frequency RFQ, possibly combined with 24-MHz superconducting interdigital structures. Beam dynamics studies of the whole low-charge-state post-accelerator section were carried out in early FY 1995.

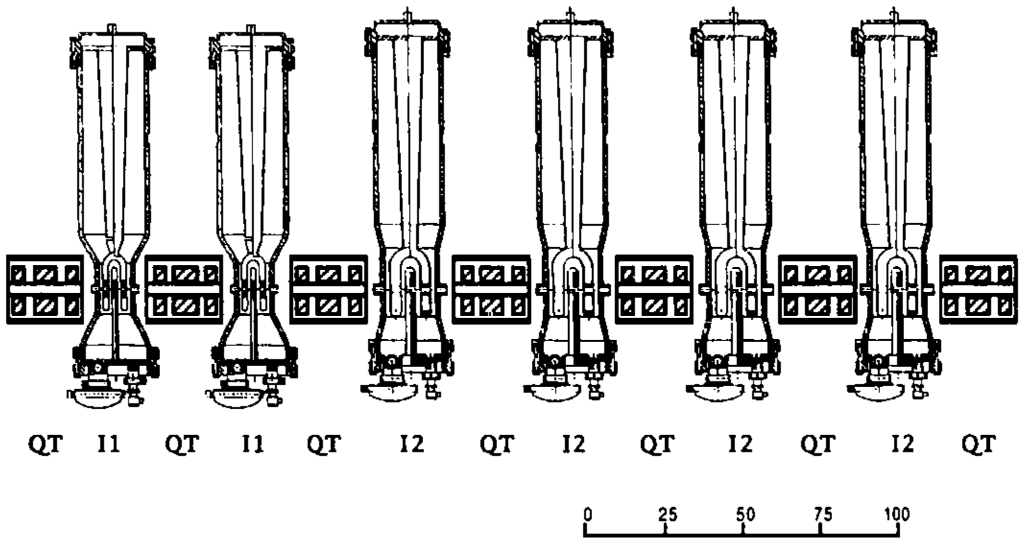

Fig. II-8. Typical section of a low q/m (1/66) suprconducting linac utilizing 48-MHz 4-gap resonators as currently used in PII and high gradient quadrupole triplets as discussed above.

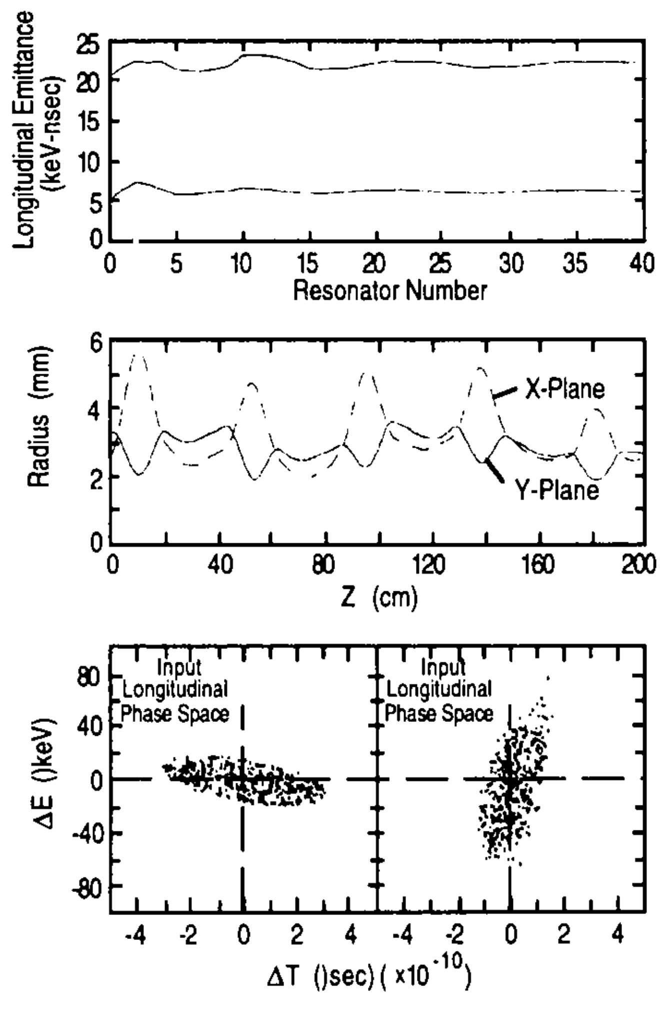

Fig. II-9. Beam dynamics calculations for q/m = 1/66 and normalized emittance of 0.25 π mm-mr with the layout illustrated in Fig. II-8.

c. Low-charge-state RFQ Injector
(K. W. Shepard and J. W. Kim)

Preliminary design work was done for a short, normally-conducting RFQ entrance section for a low-charge-state linac. Early results indicate that a low-frequency (12 MHz) RFQ, operated on a high-voltage platform, and injected with a pre-bunched beam, can provide ATLAS quality beams of ions of charge-to-mass ratio less than 1/132.

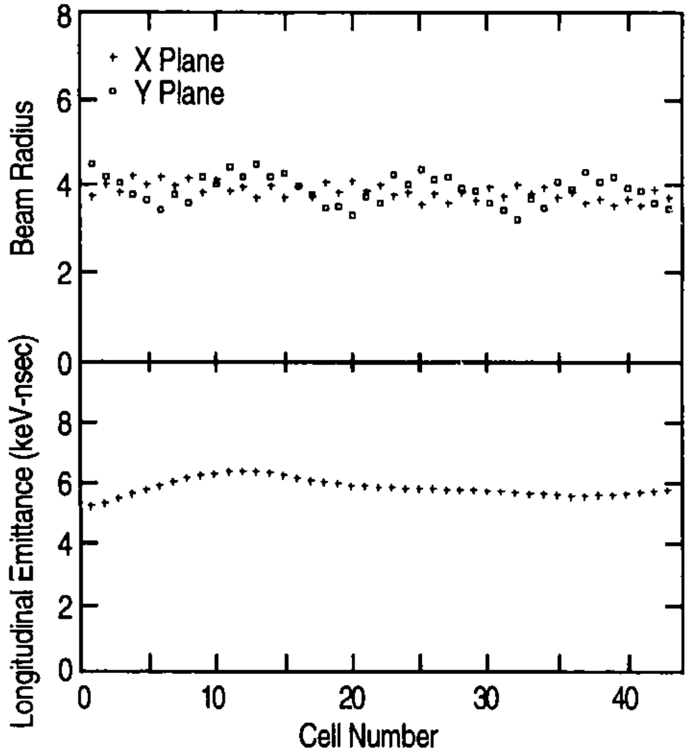

Fig. II-10. Beam dynamics calculation for a 12 MHz normally conducting RFQ appropriate for use to preaccelerate radioactive ions with q/m = 1/132 and normalized emittance of 0.25 π mm-mr.

d. Charge-State Enhancement for Radioactive Beam Post-Acceleration
(J. A. Nolen and J. Dooling)

A critical question for an ISOL-type radioactive-beam facility, such as that being discussed by the North American Isospin Laboratory Committee, is the efficiency and q/m of the ion source for the radioactive species. ISOLDE at CERN demonstrated that high efficiency is obtained for a wide variety of species in the 1^+ charge state. These ion sources also generally have excellent transverse emittances and low energy spreads. One possibility is to use this proven technology plus an ionizer stage to increase the output of such sources to 2, 3, or 4^+ with high efficiency. We are currently investigating technical options for such charge-state enhancement. There is a proposal by a Heidelberg/ISOLDE collaboration to build a "charge-state breeder" as part of an experiment called REX-ISOLDE. This concept would deliver batches of radioactive ions with low duty cycle, optimized for relatively low-intensity secondary beams, on the order of 10^6/sec. We are independently doing simulations of an alternative approach, called the Electron-Beam Charge-State Amplifier (EBQA), which would yield DC beams with improved transverse emittance and would not have the intensity limitation of the batch transfer process. The cost and efficiency of the EBQA will have to be compared with those of a normally-conducting CW RFQ followed by ion stripping, as alternatives for the first stage of a secondary ion accelerator.

e. **Ion Sources and Targets for Radioactive Beams** (J. P. Schiffer, B. B. Back, I. Ahmad, K. E. Rehm, J. A. Nolen, K. Beyer, J. Binder,* J. Sienecki,* R. Ronningen†)

A high-intensity ISOL-type radioactive beam facility depends critically on the performance of the target/ion source system. We developed a concept for producing high-intensity secondary beams of fission fragments, such as ^{132}Sn, using a two-part target and ion source combination. The idea involves stopping a 1000-kW beam of 200-MeV deuterons in a target of Be or U to produce a secondary beam of neutrons. Just behind the neutron production target is a second target, typically a porous form of UC, coupled to an ISOL-type ion source. In December 1994, we tested this concept with 200-MeV deuterons at low intensity in an experiment at the NSCL. The yields of characteristic gamma rays were measured and confirmed our predictions.

To continue developing expertise with targets and ion sources required for an advanced ISOL-type radioactive beam facility we are obtaining a source from the TRISTAN group at Brookhaven. This source will be installed and operated at the ATLAS ion source test beam line to measure its transverse emittance and ionization efficiency. After this initial experience we plan to move the source to the Physics Division Dynamitron accelerator to produce low-intensity radioactive beams via neutron-induced fission.

Experience at the ISOLDE facility at CERN showed that liquid targets are very useful for coupling to ion sources for radioactive beam production. Liquid targets of lanthanum, gold, and lead, for example, were quite successful. However, so far a reliable liquid target of uranium was not developed. Such a target would be very useful, especially for fission products with lifetimes on the order of 30 sec or more, e.g. ^{132}Sn. Hence, we have initiated some tests in collaboration with the Reactor Engineering Division at Argonne to evaluate some alloys for liquid uranium containment. These tests are being carried out during FY 1995.

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*Reactor Engineering Division, ANL, †National Superconducting Cyclotron Laboratory.

III. MEDIUM-ENERGY NUCLEAR PHYSICS RESEARCH

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. By the end of FY 1994, all major components had been delivered to CEBAF and final assembly was underway. The SOS will be commissioned in FY 1995 and will be an important component in the first round at CEBAF experiments.

The most direct way to probe the quark structure of nuclei is to use a high-energy probe which interacts with a single quark at a time. In FNAL experiment E665, the deep inelastic scattering of 490-GeV muons at Fermi National Accelerator Laboratory measures the changes of the quark distributions in the nucleus compared to the nucleon, and the interactions of high-energy quarks and hadrons with nuclear material. New results have identified diffractive scattering for the first time in deep inelastic scattering from nuclei. Inelastic lepton scattering makes it possible to control separately the transverse and longitudinal energy scales of exclusive reactions. In exclusive ρ-meson production, a signal for color transparency is observed in the increase of the relative cross section on lead compared to that on deuterium as a function of momentum transfer squared. This complements and extends our search for color transparency in exclusive proton knock-out reactions at SLAC. New data on the ratio of deep inelastic scattering from hydrogen and deuterium show that nuclear effects are important in the deuteron but also confirm previous results which suggest that the $\bar{u}$ distributions and the $\bar{d}$ distributions are quite different. A new FNAL experiment, E866, will measure directly this difference using the Drell-Yan process in the next 1996-98 fixed-target cycle.

Considerable technical resources of the medium-energy program were 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 is in progress. At the same time, measurements are continuing at intermediate momentum transfers. The program at Novosibirsk provides a proof-of-principle for HERMES. A new effort is underway to produce a polarized tritium target for external beam experiments at CEBAF. This is a substantial extension of the laser-pumped spin-exchange technology to sealed target cells.

HERMES, a broadly-based North American-European collaboration, is studying the spin structure of the nucleon using internal polarized targets in the HERA electron storage ring at the DESY Laboratory, Hamburg, Germany. The HERMES detector is in the first stages of assembly.

Argonne contributed the Cerenkov counter which will provide the primary hadron particle identification for the experiment. Argonne also continues developing laser-pumped target technology for the hydrogen and deuterium phases of the experiment.

Activities involving the NPAS program at the Stanford Linear Accelerator Center are essentially concluded. The data from measurements of the photodisintegration of the deuteron at photon energies up to 4.2 GeV is in various stages of publication. 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 series of publications summarizing the data is in preparation.

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. Haas,¶ 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,** D. A. Averill,** 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 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.

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

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 4π 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.

Final results are available from the 1987-88 data in thirteen publications. Twenty three students completed Ph.D. theses on this experiment. Production analysis of the 1990 and 1991 data sets was completed and physics analysis is nearing completion with one paper accepted and several ready to be submitted for publication. Several new results on A dependence of deep inelastic scattering demonstrate the power and kinematic range of the experiment. From the 1991 data, the ratio of the cross section per nucleon of deuterium to hydrogen remains constant at a value of 0.97 from $10^{-4} < x < 10^{-2}$. This demonstrates the importance of shadowing even in the A=2 system.

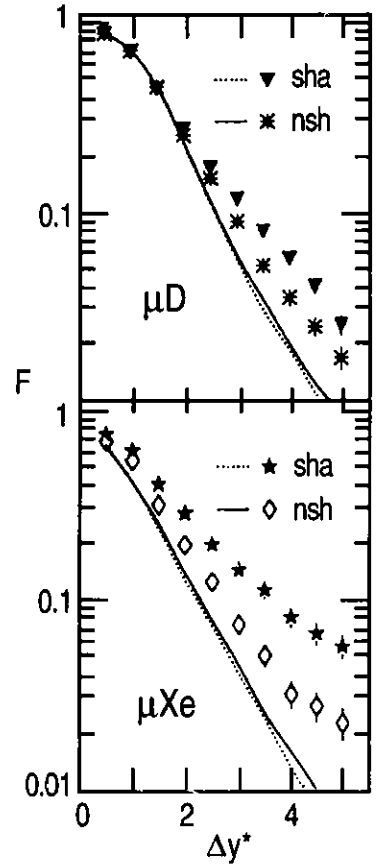

Fig. III-1. The fraction, F, of events from deep inelastic muon scattering from Xe and deuterium targets with the slowest detected hadron at a rapidity greater than the target rapidity by Δy for events with x > 0.02 (nsh) and events with x < 0.02. The curves are the expectations from string fragmentation models.*

In another new result, the reinteractions of the hadronic debris following deep inelastic scattering was studied in the streamer chamber pictures. By any of three measures: the average net charge, the number of intermediate energy protons, and the backwards multiplicity, there is less cascading of the nuclear debris in the shadowing region than at higher x. The underlying cause of this behavior was identified by examining the hadron event structure. At low x, a new reaction mechanism, diffractive scattering, becomes important and contributes up to 20% of the total inelastic cross section on xenon.[1] These events are identified as having a large gap in rapidity between the target rapidity and the lowest rapidity detected hadron. The fraction of events with a rapidity gap greater than Δy^* is shown in Figure III-1. The relationship between shadowing and diffractive scattering is now being studied in QCD-based models.

In a related diffractive process, exclusive ρ vector-meson production at high energy, one can control independently the transverse size (Q^2) and the longitudinal extent (E_ρ). This makes these reactions particularly suited for studying the color-screening effects expected at short distance scales. E665 observed that the relative transparency of the ρ-mesons through the nucleus increases with Q^2 from 0.1 (GeV/c)^2 to 6 (GeV/c)^2. These results complement other searches for color transparency in the (e,e'p) and (p,2p) reactions. In these latter reactions the momentum and energy transfer are completely coupled and no clear transparency signal has yet been observed. Several theoretical papers have suggested that exclusive vector-meson production is the simplest and

[1]M. R. Adams et al., Z. Phys. C65, 225 (1995).

clearest channel to search for color transparency and this seems well borne out by the E665 data. Further work continues measuring the polarization of the ρ's from the angular distribution of the two-pion decay. Preliminary results suggest that the polarization of the ρ's changes from transverse to predominantly longitudinal at the larger momentum transfers. The HERMES experiment will be very well suited to extend these studies in the near future.

The 1991 data provide substantive new information on the structure functions of hydrogen and deuterium at low x. E665 observes that the structure functions below Q^2 of 1 $(GeV/c)^2$ become essentially independent of x and then appear to continue smoothly into the much higher Q^2 measurements at HERA.

Argonne scientists are concentrating on A dependence studies of jet production, diffraction, exclusive vector meson production and strangeness production. Analysis efforts are expected to continue for the next two years.

b. Electron-Deuteron Scattering With a Polarized Deuterium Gas Target in the VEPP-3 Electron Storage Ring (C. E. Jones, J. A. Fedchak, R. S. Kowalczyk, D. H. Potterveld, L. Young, B. Zeidman, R. J. Holt,* K. P. Coulter,† R. Gilman,‡ E. R. Kinney,§ S. I. Mishnev,¶ D. M. Nikolenko,¶ 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||)

The collaborative effort between Argonne and the Budker Institute for Nuclear Physics in Novosibirsk to measure the tensor analyzing power of the deuteron at high momentum transfer continues. This measurement allows the experimental separation of the deuteron charge and quadrupole form factors, which cannot be obtained from unpolarized scattering alone. Phase 2 of the experiment, which used a storage cell fed by an atomic beam source as the internal target, was completed. The limited statistics collected in this phase of the experiment are insufficient to confirm the existing data from MIT-Bates in the kinematic region up to $q = 5\ fm^{-1}$. It was decided to change to Phase 3 of the experiment, which uses a laser-driven polarized deuterium source and a passive storage cell as the target. All necessary parts of the Argonne source were delivered to Novosibirsk and work is underway to construct and test the target.

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*University of Illinois, †University of Michigan, ‡Rutgers University, §University of Colorado, ¶Budker Institute for Nuclear Physics, Novosibirsk, Russia, ||NIKHEF, Amsterdam, The Netherlands.

c. Laser-Driven Polarized Hydrogen and Deuterium Internal Targets
C. E. Jones, J. A. Fedchak, R. S. Kowalczyk, T. G. O'Neill, B. Zeidman, R. J. Holt,* and D. K. Toporkov†)

After completing comprehensive tests of the performance of the source with both hydrogen and deuterium gas, we began tests of a realistic polarized deuterium internal target. These tests involve characterizing the atomic polarization and dissociation fraction of atoms in a storage cell as a function of flow and magnetic field, and making direct measurements of the average nuclear tensor polarization of deuterium atoms in the storage cell. Transfer of polarization from the atomic electron to the nucleus as a result of D-D spin-exchange collisions was observed in deuterium, verifying calculations suggesting that high vector polarization in both hydrogen and deuterium can be obtained in a gas in spin temperature equilibrium without inducing RF transitions between the magnetic substates (see Figure III-2). In order to improve the durability of the system, the source glassware was redesigned to simplify construction and installation and eliminate stress points that

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*University of Illinois, †Budker Institute for Nuclear Physics, Novosibirsk, Russia.

led to frequent breakage. Improvements made to the nuclear polarimeter, which used the low energy $^3H(d,n)^4He$ reaction to analyze the tensor polarization of the deuterium, included installing acceleration lenses constructed of wire mesh to improve pumping conductance, construction of a new holding field coil, and elimination of the Wien filter from the setup. These changes substantially simplified operation of the polarimeter and should have reduced depolarization in collisions with the wall. However, when a number of tests failed to show an improvement of the nuclear polarization, it was discovered that extended operation of the system with a section of teflon as a getter for potassium caused the dissociation fraction to decline with time under realistic operating conditions, suggesting that teflon may not be a suitable material to eliminate potassium from the target. Currently, we are replacing the teflon surfaces with drifilm-coated ones and plan to continue tests of the polarized internal target in this configuration.

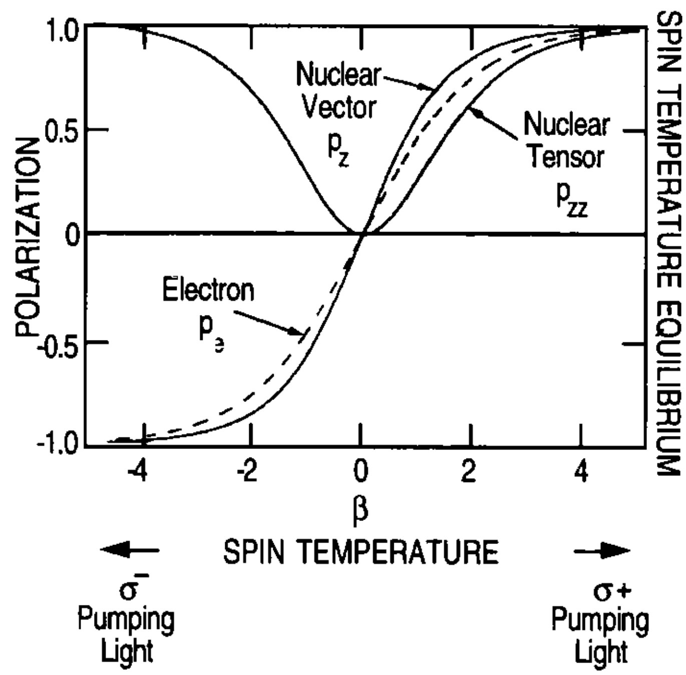

Fig. III-2. Equilibrium values of the electron, nuclear vector, and nuclear tensor polarization under conditions where the magnetic substates of deuterium have a spin temperature distribution.

d. Two-Body Photodisintegration of the Deuteron at High Energy: Experiment NE17 at SLAC (D. F. Geesaman, H. E. Jackson, J.-O. Hansen, C. E. Jones, N. C. Makins, T. G. O'Neill, V. Papavassiliou, D. H. Potterveld, B. Zeidman, D. Beck,* R. J. Holt,* K. P. Coulter,† E. R. Kinney,‡ R. Arnold,§ P. Bosted,§ C. Keppel,§ A. Lung,§ S. Rock,§ M. Spengos,§ L. H. Tao,§ J. White,§ Z. Szalata,§ M. Epstein,¶ D. Margaziotis,¶ J. Arrington,¶ E. Beise,|| J. E. Belz,|| B. Filippone,|| H. Gao,|| W. Lorenzon,|| R. McKeown,|| B. Mueller,|| J. Napolitano,**P. Anthony,‡‡ K. V. Bibber,‡‡ F. Dietrich,‡‡ M. Chapman,§§ R. Ent,§§ K. Lee,§§ R. Milner,§§ J. Nelson,§§ S. Kuhn,§§ Z.-E. Meziani,§§ G. Petratos,§§ R. E. Segel,¶¶ J. van den Brand,|| || and H. Bulten|| ||)

Experiment NE17 was granted three days of beam time during the last NPAS run at SLAC. During that time, the cross section data for the $\gamma d \rightarrow pn$ reaction were extended up to 2.8 GeV at $\theta_{cm} = 90^\circ$ and up to 4.2 GeV at $\theta_{cm} = 37^\circ$. Data were also taken at $\theta_{cm} = 37^\circ$, 53°, and 90° at $E_\gamma = 1.6$ GeV so that a complete angular distribution would be available at this energy where an enhancement at a large angle (143°) was found during experiment NE8. The results indicate the surprising feature that the cross sections at 90° and 53° follow the quark counting rule prediction, while those at 37° do not. Perhaps this indicates that p_T^2 is a controlling variable in the approach to asymptotic scaling. A manuscript was accepted for publication.

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*University of Illinois, †University of Michigan, ‡University of Colorado, §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.

e. Nuclear and Q^2 Dependence of Quasielastic (e,e'p) Scattering at Large Momentum Transfer (H. E. Jackson, D. F. Geesaman, C. E. Jones, V. Papavassiliou, D. Potterveld, B. Zeidman, D. Beck,* R. Holt,* K. Coulter,† E. R. Kinney,‡ J. Arrington,§ J. E. Belz,§ H. Gao,§ R. D. McKeown,§ B. Mueller,§ T. G. O'Neill,§ E. Beise,§ B. Filippone,§ W. Lorenzon,§ R. Arnold,¶ P. E. Bosted,¶ C. E. Keppel,¶ A. Lung,¶ M. Spengos,¶ L. H. Tao,¶ J. L. White,¶ S. Rock,¶ Z. Szalata,¶ M. Epstein,# D. Margaziotis,# J. J. Napolitano,|| R. C. Minehart,** M. S. Chapman,†† R. Ent,†† J.-O. Hansen,†† K. Lee,†† N. C. R. Makins,†† R. Milner,†† J. Nelson,†† H. J. Bulten,§§ J. van den Brand§§ P.L. Anthony,¶¶ K. van Bibber,¶¶ F. S. Dietrich,¶¶ S. E. Kuhn,## R. A. Gearhart,|| || and G. G. Petratos,|| ||)

An experiment was completed at the Stanford Linear Accelerator Center in which measurements of the (e,e'p) coincidence quasielastic cross section in nuclei were 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 $(GeV/c)^2$. Several papers describing the results were published or submitted. Analysis of the data is in its final stages. In summary, the cross section for quasielastic ^{12}C(e,e'p) scattering was measured at momentum transfer Q^2 = 1, 3, 5, and 6.8 $(GeV/c)^2$. The results are consistent with scattering from a single nucleon as the dominant process. The nuclear transparency is obtained and compared with theoretical calculations that incorporate color transparency effects. No significant rise of the transparency with Q^2 is observed. Cross sections were reported for the reaction ^2H(e,e'p)n for momentum transfers in the range $1.2 \leq Q^2 \leq 6.8$ $(GeV/c)^2$ and for missing momenta from 0 to 250 MeV/c. The longitudinal-transverse interference structure function was separated at Q^2 = 1.5 $(GeV/c)^2$. The observables were compared to calculations performed in nonrelativistic and relativistic frameworks. The data are best described by a fully relativistic calculation (see Figure III-3). The A-dependence of the quasielastic A(e,e'p) reaction was studied with ^2H, C, Fe, and Au nuclei at momentum transfers Q^2 = 1, 3, 5, and 6.8 $(GeV/c)^2$. The nuclear transparency T(A,Q^2), a measure of the average probability that the struck proton escapes from the nucleus A without interaction, was extracted. Several calculations predict a significant increase in T with momentum transfer, a phenomenon known as color transparency. No significant rise within errors is seen for any of the nuclei studied.

*Univ. of Illinois, †Univ. of Michigan, ‡Univ. of Colorado, §California Inst. of Technology, ¶American Univ., #California State Univ., ||Rensselaer Polytechnic Inst., **Univ. of Virginia, ††Massachusetts Inst. of Technology, ‡‡Univ. of Illinois, §§Univ. of Wisconsin, ¶¶Lawrence Livermore Laboratory, ##Stanford Univ., || || SLAC.

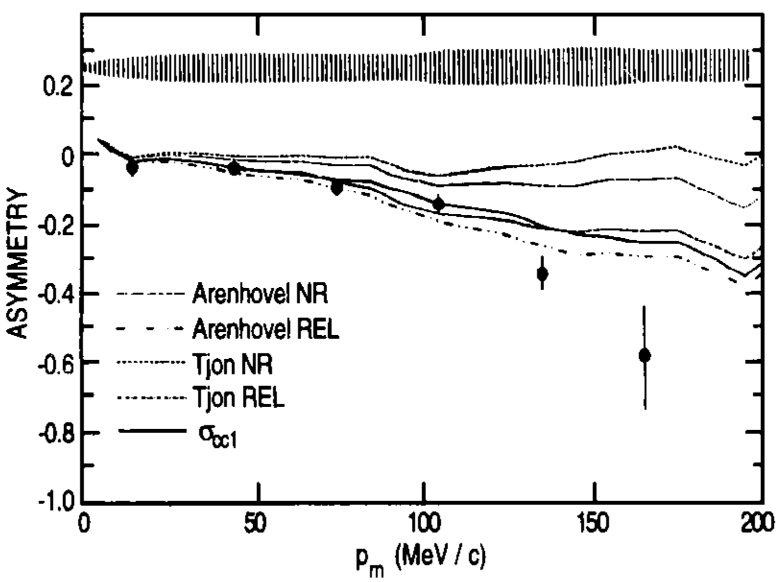

Fig. III-3. The asymmetry A_ϕ for the reaction $^2H(e,e'p)n$ as a function of the missing momentum at Q^2 = 1.2 $(GeV/c)^2$ for various non-relativistic (upper set of curves labeled NR) and relativistic (lower set of curves labeled REL) models.

f. Measurement of the Helicity-Dependent Asymmetry in $^{3}\vec{H}(\vec{e},e)$ Quasielastic Scattering (C. E. Jones, J-O. Hansen, N. C. Makins, J. Arrington,* E. J. Beise,* R. W. Carr,* B. W. Filippone,* H. Gao,* A. Lung,* R. D. McKeown,* B. Mueller,* M. Pitt,*G. Dodson,† K. Dow,† D. Deschepper,† R. Ent,† M. Farkhondeh,† W. Korsch,† L. Kramer,† K. Lee,† R. Milner,† D. Tieger,† P. Welch,† E. Candell,‡ J. Napolitano,‡ and W. Lorenzon§)

The analysis of the data from the MIT-Bates experiment in June 1993 to measure the helicity-dependent asymmetry in quasielastic scattering of polarized electrons from polarized ^{3}He was completed. The neutron magnetic form factor was extracted from data on polarized ^{3}He for the first time and is found to be in very good agreement with the dipole form at Q^2 = 0.19 (GeV/c)^2. A paper reporting the transverse asymmetry and the extracted value of the neutron magnetic form factor was published, and papers reporting the transverse-longitudinal asymmetries at the quasielastic peak (see Figure III-4) and on the low energy-transfer side of the quasielastic peak were submitted for publication.

*California Institute of Technology, †Massachusetts Institute of Technology, and Bates Linear Accelerator Center, ‡Rensselaer Polytechnic Institute, §TRIUMF, Vancouver, Canada.

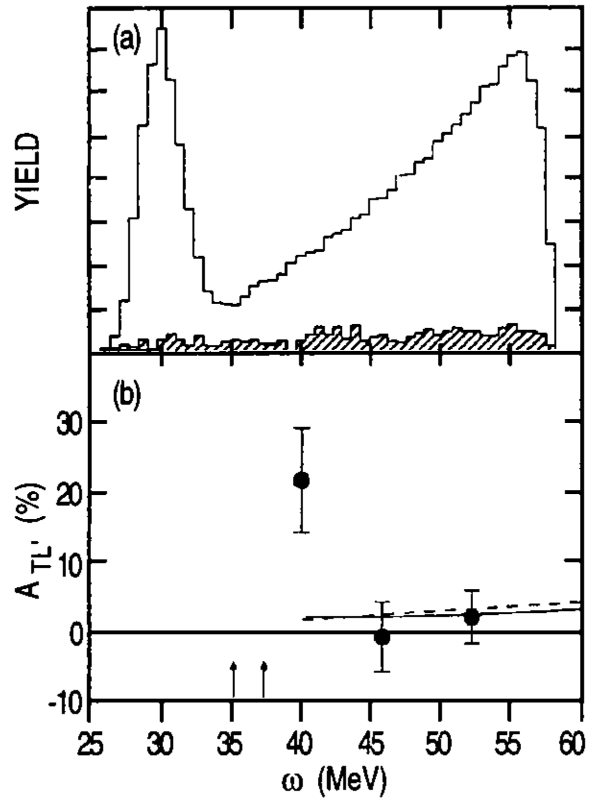

Fig. III-4. (a) Relative yield as a function of energy transfer for the target full vs. empty. The elastic peak is seen at ω = 30 MeV. (b) Measured inelastic asymmetry as a function of ω on the low-energy transfer side of the quasielastic peak. The error bars indicate the statistical uncertainty. The arrows point to the two- and three-body breakup thresholds. The curves correspond to the PWIA calculations of Schulze and Sauer (solid) and Salmé, Pace, and Ciofi degli Atti (dashed).

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

The analysis of the data from the CE25 experiment at IUCF, which measured 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, is nearing completion. At low missing momentum, the extracted polarization of the neutron and proton in ^{3}He are consistent with Faddeev calculations. Two papers, one reporting the physics results (see Figure III-5) and one describing the experiment, were published. The data from this experiment indicates that for q ≥ 500 MeV/c the plane wave impulse approximation is valid.

*Indiana University, Cyclotron Institute, †University of Wisconsin, ‡Massachusetts Institute of Technology, and Bates Linear Accelerator Center, §TRIUMF, Vancouver, Canada, ¶Ohio State University, ||Western Michigan University, **University of Louisville.

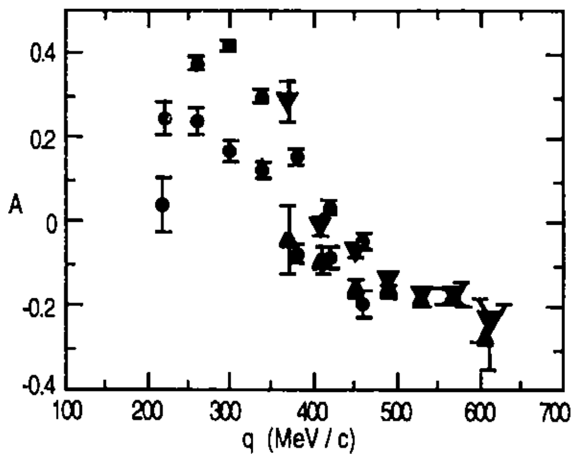

Fig. III-5. The target (filled symbols) and beam (open symbols) analyzing powers $A^{3,n}_{000n}$ and $A^{3,n}_{00n0}$ respectively, for $^3He(p,pn)$ at $|p_m| < 100$ MeV/c as a function of the 3-momentum transfer to the struck neutron |q|. Data where the proton scattered to the right (left) detector and neutrons to the left (right) detector are indicated by circular (triangular) symbols.

h. Polarized Tritium Target Development (C. E. Jones, J. A. Fedchak, and R. S. Kowalczyk)

Work began on the development of a completely sealed polarized tritium target for experiments at CEBAF. Because of the similarities between optical pumping of tritium and hydrogen, all prototype work is done with hydrogen. We constructed a test station for filling glassware with hydrogen, where we can dissociate molecular hydrogen and monitor the purity of the gas. A simple two-cell glass system was constructed, consisting of a region in which the molecular hydrogen is dissociated with an RF discharge and a region where the atoms can be optically pumped. So far, a clean discharge was obtained in the glassware. With this system, we plan to investigate ways to eliminate the discharge from the optical pumping region and test the quality of the discharge once the pumping cell is coated with drifilm.

i. Electroproduction of Kaons and Light Hypernuclei (D. F. Geesaman, H. E. Jackson, C. E. Jones, D. H. Potterveld, S. B. Kaufman, N. C. Makins, T. G. O'Neill, J. P. Schiffer, B. Zeidman, R. J. Holt,* R. E. Chrien,† S. Bart,† R. Sawafta,† R. J. Sutter,† B. Filippone,‡ W. Lorenzon,‡ J. Napolitano,§ R. Carlini,¶ R. Ent,¶ D. Mack,¶ S. A. Wood,¶ E. R. Kinney,|| O. K. Baker,** W. W. Buck,** J.-S. Cha,** L. Tang,** E. V. Hungerford,†† K. Lan,†† B. W. Mayes,†† J. J. Reidy, ‡‡ R. E. Milner,§§ R. E. Segel,¶¶ A. Klein,|| || R. Gilman***)

A detailed investigation of the basic hyperon-nucleon interactions in nuclei is one of the aims of Experiment 91-016, approved with high priority at CEBAF, to study the electroproduction of kaons on targets of deuterium, ^{3}He, and ^{4}He. Inasmuch as both the electron and K^+ are particles that interact relatively weakly with nucleons, electroproduction of light hypernuclei provides a low-distortion method for investigating the fundamental interactions between nucleons, Λ's, and Σ's in few-body systems. In particular, the (e,e'K^+) reactions on cryogenic targets of D, ^{3}He, and ^{4}He will be studied 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. Construction of the He target, operating at ~10 atm, ~50 K and capable of dissipating ~30 W, is expected to be complete prior to commencement of production runs in Hall C. The first data runs for E91-016, expected to begin late in FY 1995, will also be the basis for a doctoral thesis at Hampton University. In addition to providing new information on the phases of hyperon-nucleon interactions, measurements of cross sections for hypernuclear formation, and interference phenomena, the data may provide evidence for the presence of bound Σ's and strange di-baryonic states that are the subject of considerable theoretical discussion.

*Univ. of Illinois, †Brookhaven Nat'l. Laboratory, ‡California Inst. of Technology §Rensselaer Polytechnic Inst., ¶CEBAF, ||Univ. of Colorado, **Hampton Univ. ††Univ. of Houston, ‡‡Univ. of Mississippi, §§Massachusetts Insti. of Technology, ¶¶Northwestern University, || ||Old Dominion University, ***Rutgers University.

j. Two-Body Photodisintegration of the Deuteron at Forward Angles and Photon Energies Between 1.5 and 4.0 GeV (D. F. Geesaman, H. E. Jackson, S. Kaufman, D. Krakauer, D. H. Potterveld, B. Zeidman, K.P. Coulter,* E. R. Kinney,† J. Napolitano,‡ R. Carlini,§ R. Gilman,¶ R. E. Segel,|| P. Bosted,** E. Beise,†† B. Filippone,†† R. D. McKeown,†† R. Milner,‡‡ D. Beck,§§ R. J. Holt,§§ Z.-E. Meziani,¶¶ R. Minehart,|| || O. Keith Baker,*** and S. J. Freedman†††)

It was discovered in experiments NE8 and NE17 at SLAC that the differential cross section near $\theta_{cm} = 90^\circ$ for the $\gamma d \rightarrow pn$ reaction at the highest measured photon energies (E_γ = 1.3-2.8 GeV) has an energy dependence consistent with the constituent counting rules. Experiment NE17 at SLAC indicates the s-dependence of the cross section is not consistent with constituent counting at forward angles.

At CEBAF we 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 accepted by CEBAF PAC4 and was recently accorded high scientific priority by PAC7.

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 falloff 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 practical at CEBAF with the large beam current (~ 30 μA) and the large solid-angle spectrometer (HMS in Hall C). In particular, the CEBAF experiments will permit exploration of not only the scaling with photon energy, but also the transverse momenta in the reaction process. This experiment was selected as one of the commissioning experiments in Hall C and should take data in 1995.

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*University of Michigan, †University of Colorado, ‡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, †††University of California at Berkeley.

k. A Study of Longitudinal Charged-Pion Electroproduction in D, ^{3}He, and ^{4}He (H. E. Jackson, K. P. Coulter, D. F. Geesaman, S. Kaufman, D. Potterveld, B. Zeidman, R. J. Holt,* 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 electroproduction amplitudes in the forward direction. The data provide the first experimental indications for a significant change in the pion-nucleon coupling for nucleons bound in nuclei. It is clear that forward-angle electroproduction may be a sensitive probe of the properties of the pion coupling in the nuclear medium. 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 sensitivity of longitudinal electroproduction to nuclear binding effects. If current conceptions of

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*University of Illinois, †Rutgers University, ‡University of Colorado, §CEBAF ¶CEN Saclay, France, ||Northwestern University.

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 was 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.

ℓ. **The Energy Dependence of Nucleon Propagation in Nuclei as Measured in the (e,e'p) Reaction** (D. F. Geesaman, J. A. Fedchak, J.-O. Hansen, H. E. Jackson, C. E. Jones, S. Kaufman, N. C. Makins, T. G. O'Neill, D. Potterveld, J. P. Schiffer, B. Zeidman, R. J. Holt,* D. Dutta,† R. E. Segel,† E. R. Kinney,‡ D. van Westrum,‡ J. Arrington, § B. W. Filippone,§ R. D. McKeown,§ R. Milner,¶ L. Baker,|| J. Cha,|| L. Tang,|| K. Beard,|| T. Eden,|| R. Madey,|| R. Gilman,** R. Carlini,†† R. Ent,†† D. Mack,†† J. Mitchell,†† S. Wood,†† C. Yan,†† D. Meekins,‡‡ T. Amatoni,§§ H. Mkrtchyuan,§§ V. Tadevosian,§§ D. Beatty,¶¶ S. Barrow,¶¶ Z. Mao,¶¶ W. Lorenzon,¶¶ T. Fortune,¶¶ and C. Keppell ||)

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. At higher energies, this reaction is used to study manifestations of more exotic mechanisms, such as increased transparency for hard collisions - color transparency.

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. The collaboration developing the equipment for Hall C has chosen this experiment to be the tune-up experiment and the first experiment to be performed at CEBAF. It is expected to receive beam in Spring 1995.

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*University of Illinois, †Northwestern University, ‡University of Colorado, §California Institute of Technology, ¶Massachusetts Institute of Technology ||Hampton University, **Rutgers University, ‡‡College of William and Mary §§Yerevan Physics Institute, Yerevan, Armenia, ¶¶University of Pennsylvania || ||Virginia Union University.

m. Measurement of Proton Polarization in the d(γ,p)n Reaction (D. F. Geesaman, H. E. Jackson, C. E. Jones, D. Krakauer, D. H. Potterveld, B. Zeidman, K. P. Coulter,* 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,†† D. Beck,‡‡ R. J. Holt,‡‡ and S. J. Freedman§§)

A proposal was approved by CEBAF PAC7 to measure angular distributions of the proton polarization for the $d(\gamma,\vec{p})n$ reaction in the GeV region. This proposed measurement will test the validity of extensions of conventional nuclear-physics theories to the higher energy regime. The results of the experiment will further constrain the evidence from SLAC experiments NE8 and NE17 that asymptotic scaling was observed above a photon energy of 1.3 GeV. Photoproton polarization measurements at lower energy indicate that the magnitude of the polarization increases with energy. This is consistent with the observation that polarizations are large in high-energy processes, e.g. A_{nn} in pp → pp scattering or A_y in pp → π^0X. However, the polarizations in hadron-hadron scattering are believed to arise from Landshoff mechanisms. The higher energy photoproton experiment will permit the first measurements of polarization for a reaction, $\gamma d \rightarrow \vec{p}n$, where there are no Landshoff terms. 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.

*University of Michigan, †University of Colorado, ‡California Institute of Technology, §Rensselaer Polytechnic Institute, ¶Massachusetts Institute of Technology, ||Northwestern University, **Rutgers University, ††Stanford University, ‡‡University of Illinois, §§University of California at Berkeley.

n. Short-Orbit Spectrometer for Hall C at CEBAF (H. E. Jackson, D. H. 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, the Argonne group has built, under contract to CEBAF, a short-orbit spectrometer, the SOS, based on a $QD\overline{D}$ design. 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 < 5 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 was 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. Operation of SOS in conjunction with the High Momentum Spectrometer in Hall C will provide a coincidence capability and will serve as a general-purpose second arm in a wide variety of experiments planned at CEBAF. The spectrometer is in the final stages of assembly and is scheduled to receive beam for commissioning in spring 1995 (see Figure III-6).

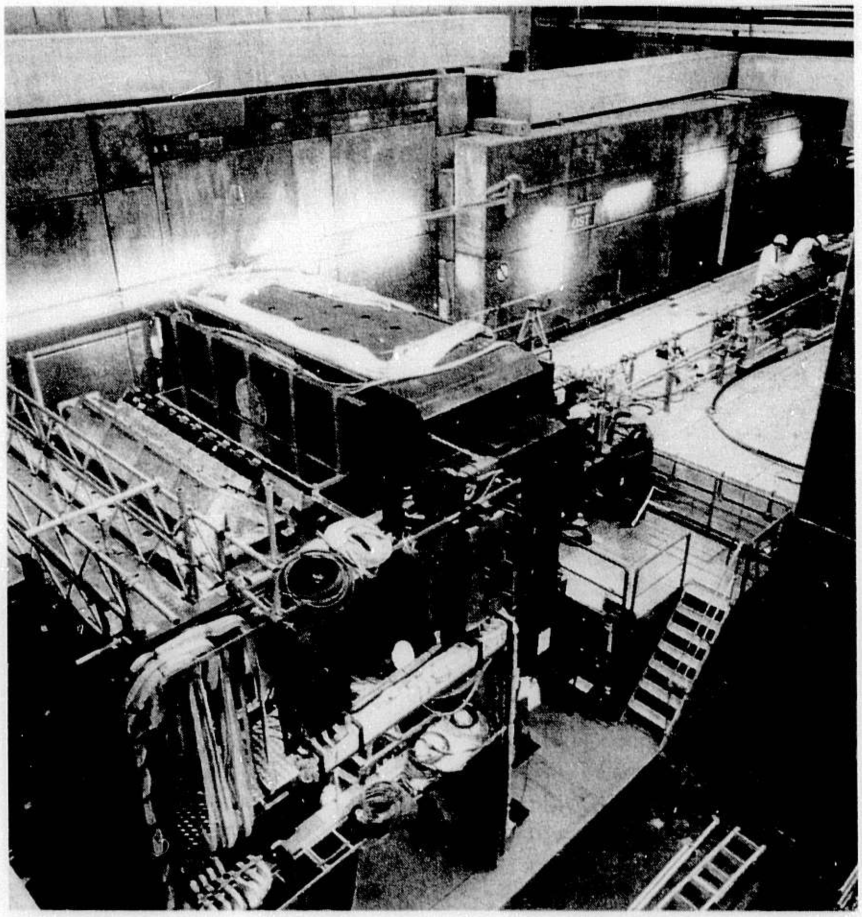

Fig. III-6. Short-orbit spectrometer in final stage of assembly in Hall C at CEBAF.

o. ³He Target for Hall C at CEBAF (B. Zeidman and A. Zeuli)

A major fraction of the physics program for Hall C involves scattering from cryogenic targets of the lightest nuclei, i.e. H, D, and ^{3,4}He. Argonne is constructing the He target that will consist of a 4cm cylinder, operating at a pressure of 10 atmospheres and a temperature of ~5.2 degrees Kelvin. CEBAF is currently constructing a cryo-target system for liquid H and D cells and the cooled, pressurized helium targets. The He target system includes cell loop, the He supply systems, and the additional equipment needed to ensure minimum loss of ^{3}He in the event of target rupture. Some of the major components have been completed, while the balance of the system will be ready for installation this fiscal year.

p. Proposal to Measure Spin-Structure Functions and Semi-Exclusive Asymmetries for the Proton and Neutron at HERA (H. E. Jackson, J.-O. Hansen, C. E. Jones, N.C.R. Makins, T. G. O'Neill, D. H. Potterveld, and collaborators at 27 other institutions)

Nucleon spin physics will be studied in the HERMES experiment, that will use polarized internal targets of essentially pure atomic H, D, and ^{3}He in the HERA electron storage ring at DESY. A series of measurements of spin-dependent properties of the nucleon and few-body nuclei will be made; the spin structure function $g_1(x)$ of the proton and neutron will be measured to test the Bjorken sum rule and study the fraction of the nucleon spin carried by quarks; the spin structure function $g_2(x)$, sensitive to quark-gluon correlations, and the structure functions $b_1(x)$, and $\Delta(x)$, sensitive to nuclear binding effects, will be measured; and, using the particle identification capability of the HERMES detector, pions will be detected in coincidence with the scattered electrons. The coincident hadron measurements represent the most important extension that can be made at this time to the existing measurements on the nucleon spin structure functions because they provide information about the flavor-dependence of the quark spin distribution in the nucleon. Argonne is providing the Cerenkov counter to be used for particle identification and developing the drifilm coating technique for the ultrathin target cell required for this experiment. The HERMES collaboration intends to use polarized targets with the highest available figures of merit, and the Argonne laser-driven source offers the most promise for a significant advance in present-day targets.

During the summer of 1994, a series of engineering tests were carried out with a prototype target cell and prototype detector components. Data were gathered on target-beam interactions - the effects on the target on beam lifetime and emittance. It was established that HERMES will be able to run concurrently with the collider experiments, H1 and ZEUS. Data were also acquired on projected backgrounds expected in the HERMES spectrometer in normal operation. Measurements were continued of the positron beam polarization. With spin rotators in place and functioning,

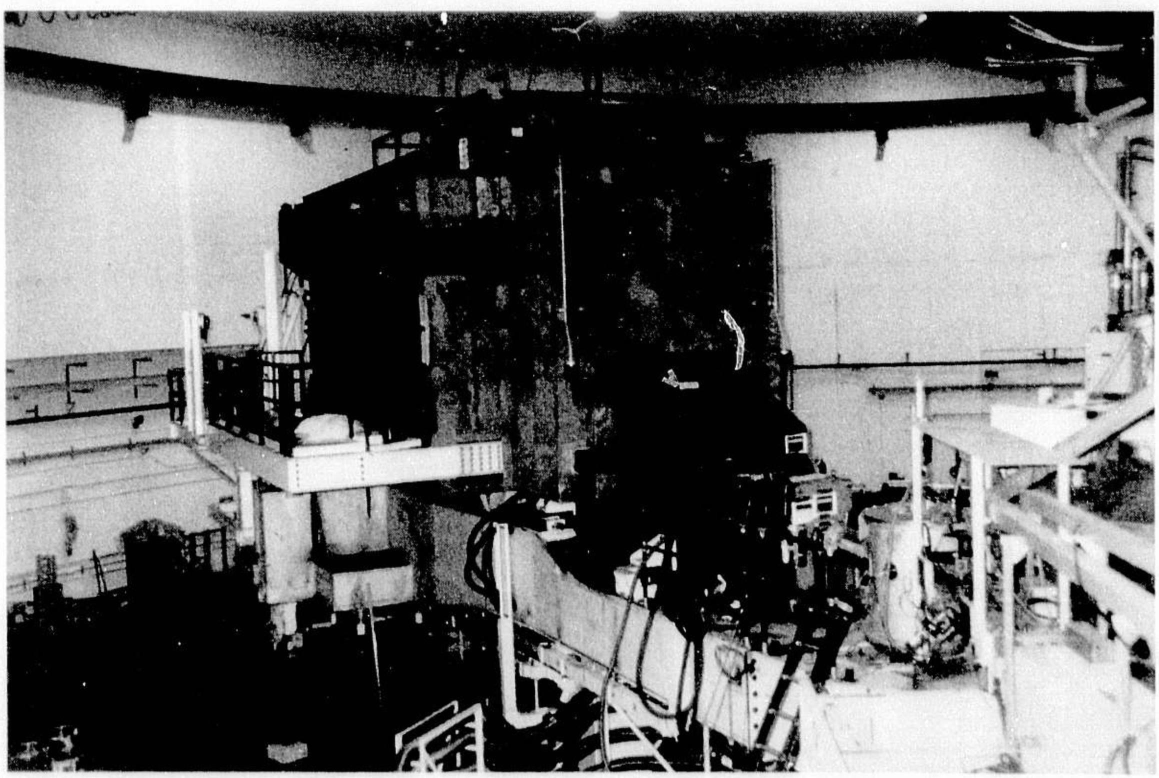

Fig. III-7. The HERMES spectrometer.

beam polarizations in excess of 60% were reproducibly obtained. Assembly of the HERMES spectrometer (see Figure III-7) is essentially complete and roll-in to the intersection is scheduled for March 1, 1995. The experiment is scheduled to receive first beam during April 1995, and data acquisition will begin shortly thereafter, continuing until about December 1, 1995. The collaboration has agreed to devote the first year of operation to studies of the neutron using the ^{3}H polarized target.

q. Measurement of $\bar{d}/\bar{u}$ in the Nucleon (D. F. Geesaman, J.-O. Hansen H. E. Jackson, S. Kaufman, N. C. Makins, V. Papavassiliou, B. Zeidman, D. Isenhower,* M. Sadler,* Y. C. Chen,† G. C. Kiang,† P. K. Teng,† M. J. Wang,† B. Filippone,‡ R. McKeown,‡ C. N. Brown,§ W. E. Cooper,§ C. S. Mishra,§ T. A. Carey,¶ G. T. Garvey,¶ D. M. Jansen,¶ M. J. Leitch,¶ J. B. McClelland,¶ P. L. McGaughey,¶ C. L. Morris,¶ J. M. Moss,¶ J. C. Peng,¶ D. M. Kaplan,|| T. C. Awes,** F. E. Obenshain,** G. R. Young,** F. Z. Plasil, ** Hee Kim,** S. Saini,** P. Stankus,** S. P. Sorenson,†† C. A Gagliardi,‡‡ and R. E. Tribble‡‡)

Recent experimental results on the deep inelastic structure functions on hydrogen and deuterium, combined in a sum rule analysis, suggest that there is a substantial difference between the $\bar{u}$ and $\bar{d}$ sea in the proton. The Drell-Yan process, where a quark from a projectile annihilates with an anti-quark in the target to form a timelike-virtual-photon, can provide a direct measurement of the x dependence of the antiquark distributions. A first examination of this process in CERN experiment NA-51 confirmed that the $\bar{u}$ and $\bar{d}$ distributions are indeed different near x of 0.15.

A new experiment, E866, was approved for the next fixed target cycle at FNAL to measure accurately the Drell-Yan production of di-muon pairs using an 800 GeV proton beam on liquid hydrogen and deuterium targets with relative systematic errors of ~1%. This will measure $\bar{d}/\bar{u}$ to 1% accuracy for $0.05 < x < 0.15$ and with lesser statistical accuracy out to $x \sim 0.3$, with one to two orders of magnitude higher statistics than NA-51. High statistics J/ψ, and ψ' and ϒ production data will also be obtained.

It is expected that the experiment will begin to take data in FY 1996 and continue in FY 1997.

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*Abilene Christian University, †Academia Sinica, Taiwan, ROC, ‡California Institute of Technology, §Fermi National Accelerator Laboratory, ¶Los Alamos National Laboratory, ||Northern Illinois University, **Oak Ridge National Laboratory, ††University of Tennessee, ‡‡Texas A&M University.

IV. THEORETICAL PHYSICS

Theoretical nuclear research at Argonne addresses a broad range of problems involving the structure and dynamics of hadrons and nuclei. There is a strong emphasis on comparison to data provided by experimental groups at Argonne and at other facilities around the world. The principal areas of research include nuclear dynamics with sub-nucleonic degrees of freedom, nuclear forces and nuclear systems, and heavy-ion reactions and nuclear structure studies. Our work includes the modeling of quantum chromodynamics in meson and baryon structure, developing reaction theories for medium-energy nucleon-nucleon interactions and meson production, and studying electron scattering within the framework of relativistic Hamiltonian particle dynamics. We also construct realistic nucleon-nucleon potentials that give very accurate fits to elastic scattering data, and then use these in detailed many-body calculations of the properties of few-body nuclei, light closed-shell nuclei, hypernuclei, nuclear matter and neutron stars. Heavy-ion research includes the structure and reactions of neutron-rich nuclei produced at radioactive beam facilities and coupled-channels calculations of reactions near the Coulomb barrier, while our nuclear structure research concentrates on effective two-body interaction studies of deformed and superdeformed nuclei observed at ATLAS. Several of these projects require major numerical simulations using state-of-the-art computers, including Argonne's massively parallel IBM SP. Much of our work is done in collaboration with other researchers at domestic and foreign universities and other national laboratories.

A. NUCLEAR DYNAMICS WITH SUBNUCLEONIC DEGREES OF FREEDOM

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

We are continuing our effort to investigate intermediate energy reactions based on a meson-exchange model which was developed over the years by carrying out extensive studies of πN, γN, NN, and πd reactions. This year we succeeded in determining the crucial πNN form factor of the model from the most recent data of threshold pion production in pp scattering, and extending the model to include the heavy meson-exchange in $N\Delta$ channels and the short-range mechanisms predicted by the chiral quark model. The constructed model has been applied to investigate electroproduction of pions on the three-nucleon systems, proton-proton Bremsstrahlung, $pp \rightarrow \pi^+ d$ at high energies, and the effects of the Δ three-body force on effective interactions of the nuclear shell-model. The model is being extended to investigate the electroproduction of vector mesons at high energies in conjunction with the new experimental initiatives at HERMES and CEBAF.

We made extensive progress in employing the Dyson-Schwinger equations (DSEs) as a semi-phenomenological tool for nonperturbative studies of QCD. The DSE approach is both an alternative and complement to numerical simulations of the lattice-QCD Lagrangian. In the course of this research we have undertaken nonperturbative studies of QED, which provide us with important qualitative input for our QCD studies and contribute to a deeper understanding of the application of this approach to the solution of gauge field theories. Important recent successes are the calculation of the electromagnetic pion form factor of the $\gamma^*\pi^0 \rightarrow \gamma$ transition form factor, which manifestly demonstrates the unique ability of this approach to unify the perturbative and nonperturbative domains of QCD, where confinement and dynamical chiral symmetry breaking are crucial. We are currently applying this framework to the study of the baryon spectroscopy and electromagnetic properties.

We are continuing our investigation of electron scattering of few-nucleon systems in the framework of relativistic Hamiltonian few-body dynamics. Euclidean space-time formulations of Lagrangian quantum field theories provide the mathematical basis for nonperturbative approximations, and for precisely-defined models of finite systems. We have been exploring the implications of this approach. Independently we found that the well-known Lorentz covariant representations of current kernels for spin-1/2 and spin-1 can be generalized to arbitrary integral and half-odd integral spin by emphasizing the O(1,2) subgroup that leaves the four-momentum transfer invariant. We expect this representation to provide the basis for the construction of dynamically-determined interaction currents in the framework of Hamiltonian light-front dynamics.

a. Electromagnetic Production of Mesons and Nucleon Resonances at GeV Energies (T.-S. H. Lee, M. Pichowsky, and T. Sato*)

A coupled-channels model for investigating the electromagnetic excitation of nucleon resonances (N*) at energies accessible to CEBAF, was developed. 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. The standard projection operator technique was applied to obtain a set of unitary scattering equations for describing πN and γN reactions up to the GeV energy region. By assuming 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 constants and the range parameters of the hadronic form factors are adjusted to reproduce πN scattering phase shifts up to 2-GeV incident pion energy. We then explore the dependence of the $\gamma N \to \pi N$ and $N(e,e'\pi)$ observables on the $\gamma N \to N^*$ excitation strengths predicted by various QCD-based models of hadrons.

In the Δ-excitation region, the model is reduced to the model of Nozawa, Blankleider and Lee, which was very successful in describing extensive results of $\gamma N \to \pi N$ and $N(e,e'\pi)$ data. In FY 1995, we applied the model to investigate the $\gamma^* N \leftrightarrow \Delta$ transition form factor up to high momentum transfer $Q^2 \leq 3$ $(GeV/c)^2$. It is found that our model is consistent with the recent SLAC data. The contribution from the bare quark core is close to the values predicted by the algebraic constituent quark model of hadrons, recently developed by Bijker, Iachello and Levitan. We also applied the model to investigate the production of vector mesons. The current focus is to extract from the exclusive $p(e,e'\rho^0)p$ data the diffractive scattering amplitude parameterized as Pomeron-exchange. This amplitude is needed for investigating the strangeness content of the nucleon by using the electroproduction of ϕ-meson.

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b. Electroproduction of Pions at Threshold in Chiral Perturbation Theory (T.-S. H. Lee, V. Bernard,* N. Kaiser,† and Ulf-G. Meissner‡)

The electroproduction of pions off protons close to threshold is studied within the framework of baryon 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 was done up to the 1-loop level by carrying out order-by-order renormalization procedures. A thorough study of the low-energy theorems related to electroproduction of pions was carried out. Our study showed how the axial radius of the nucleon can be related to the S-wave multipoles $E_{0+}^{(-)}$ and $L_{0+}^{(-)}$.

The chiral perturbation theory calculations of the $\gamma^* p \to \pi^0 p$ reaction near threshold were found to be in good agreement with the recent NIKHEF data. We also investigated the influence of some

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isospin-breaking effects. For future experimental tests of the underlying chiral dynamics, extensive predictions of differential cross sectionsand multipole amplitudes were made. A paper describing our results was published. Our predictions are compared with the standard pseudo-vector Born term in Figure IV-1. We are extending the calculation to include higher-order corrections.

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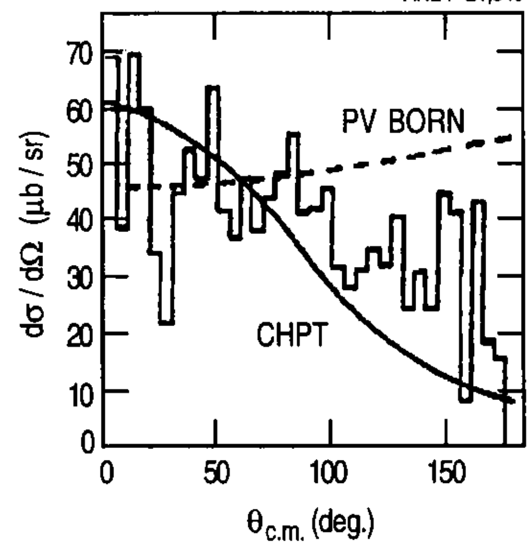

Fig. IV-1. Transverse differential cross sections of $p(ee'\pi^0)$ reaction calculated from CHPT (solid) and PV coupling (dashed).

c. A Relativistic Meson-Exchange Model of Pion-Nucleon Scattering (T.-S. H. Lee, C. T. Hung,* and S. N. Yang*)

Pion-nucleon scattering is investigated using the Kadshevsky three-dimensional reduction of the Bethe-Salpeter equation. The resulting potential includes the direct and crossed N and Δ terms, and the t-channel σ- and ρ-exchange terms. The nucleon-pole condition is imposed to define the renormalization of the nucleon mass and the πNN coupling constant. A mixture of the scalar and vector σππ couplings is introduced to simulate the broad width of the s-wave correlated two-pion exchange mechanism. Good descriptions of the πN phase shifts up to 400 MeV have been obtained in all S- and P-waves. The off-shell behavior for our model differs significantly from that obtained using different reductions. A paper describing our results was published.

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d. Unitary πNN Model (T.-S. H. Lee, F. de Jong,* G. Q. Liu,† and A. W. Thomas†)

An important feature of nuclear reactions at energies accessible to the new facilities at CEBAF and RHIC is pion production. It is important to determine the extent to which these reactions can be described in terms of color-singlet hadronic degrees of freedom. Without such a baseline, any attempt to explore QCD dynamics from such complex processes will be difficult. We are improving our earlier work on the πNN model with the π and Δ degrees of freedom to address this question. Our current focus is to improve the model by taking into account three recent developments: 1) the nonresonant pion production mechanisms were identified in the study of threshold pion production in proton-proton collisions, 2) the short-range NN and NΔ interactions can be calculated from the chiral quark model, and 3) the NN phase shifts analysis was improved and extended to 1.6 GeV. We obtained the first results showing that, by including the nonresonant pion production mechanisms of Lee and Riska, the long-standing problem concerning the NN inelasticities near threshold can be resolved. We are carrying out extensive numerical calculations to quantify the improved πNN model. The resulting model will be used to improve our many investigations of nuclear dynamics involving π and Δ degrees of freedom, as described in the following subsections.

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e. **Threshold Pion Production from Proton-Proton Collisions** (T.-S. H. Lee)

We showed that the threshold production of π^0pp, π^+np, and π^+d from proton-proton collisions can be consistently described by a model consisting of pion s-wave rescattering and $N\bar{N}$ pair-terms of heavy-meson exchanges. The large difference between $\sigma^{tot}(pp \rightarrow \pi^+ d)$ and $\sigma^{tot}(pp \rightarrow \pi^+ np)$ is understood from the orthogonality of the deuteron and the np scattering wave functions. In a calculation using the Paris potential, we find that the data can be reproduced best by using a soft πNN form factor with $\Lambda = 650$ MeV for a monopole form. This is consistent with our earlier studies of pion production in the Δ-excitation region. A paper describing this result was submitted for publication. Our results for total cross sections are shown in Figure IV-2.

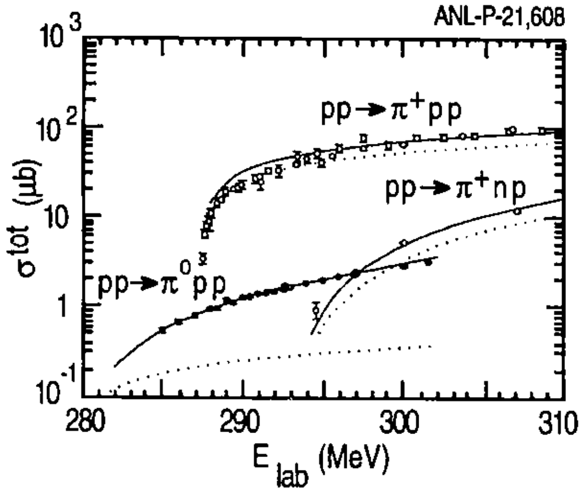

Fig. IV-2. The total cross sections (solid curves) calculated using the Paris potential and $g_\sigma^2/4\pi=16, \Lambda_\sigma =$ 2000 MeV/c for the σ–exchange model of A_α are compared with the data. The dotted curves do not include the NN pair-terms of heavy meson exchanges.

f. **Two-Body Pion Absorption on ^{3}He at Threshold** (T.-S. H. Lee, L. L. Kiang,* and D. O. Riska†)

We showed that a drastic reduction of the ratio of the rates of the reactions $^3He(\pi^-,nn)$ and $^3He(\pi^-,np)$ for stopped pions is obtained once the effect of the short-range two-nucleon components of the axial charge operator for nuclear systems is taken into account. In a calculation using realistic models of nucleon-nucleon interactions in the construction of these short-range components of the axial charge operator, the predicted ratios can be brought to within 10-20% of the empirical value. A paper describing our results was published.

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g. **Electroproduction of Pions on the Three-Nucleon Systems** (T.-S. H. Lee, C. Chmielewski,* P. U. Sauer,* G. A. Miller,† and M. Strikman‡)

The electroproduction of pions on ^{3}He is being studied with the assumption that the basic pion production mechanisms can be described by the N(e,e'π) model developed by Nozawa and Lee. In the impulse approximation, the ^{3}He(e,e'π) cross section is then determined from the N and Δ spectral functions generated from Hannover's three-body calculation including the Δ. The objective is to investigate the effects due to the Δ components in ^{3}He, as suggested by Lipkin and Lee. This is being investigated by calculating the ratio between ^{3}He(e,e'π^+p) and ^{3}He(e,e'π^-). In a calculation for ^{3}He(e,e'π^+p) at very high momentum transfer, questions concerning color transparency of Δ^{++} propagation can be addressed.

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h. The Effect of the Δ Excitation on Proton-Proton Bremsstrahlung (T.-S. H. Lee, F. de Jong,* and K. Nakayama*)

The proton-proton bremsstrahlung is investigated with a coupled-channel model with π and Δ degrees of freedom. The model is consistent with the NN scattering up to 1 GeV and the γNΔ vertex determined in the study of pion photoproduction on the nucleon. We find that the Δ excitation can significantly improve the agreement with the pp → ppγ data at $E_L = 280$ MeV. The NΔ rescattering plays an important role in determining the angular distribution and analyzing powers. Predictions at $E_L = 550$ and 800 MeV were made for the forthcoming experimental tests at COSY of Jülich. A paper describing our results was submitted for publication.

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i. The Effect of the Δ Three-Body Force on Effective Nucleon-Nucleon Interactions of the Nuclear Shell-Model (T.-S. H. Lee, T. T. S. Kuo,* and Y. Tzeng†)

The effect of the Δ three-nucleon force on the shell-model effective interaction is investigated by evaluating the Δ particle-nucleon hole core polarization diagrams $G_{pp\Delta h}$ within the folded-diagram formulation. The calculation has been performed using the NN ↔ NΔ transition G-matrix generated from a coupled-channel πNN model which is constrained by the NN data up to 1 GeV and is based on a Δ-subtracted Paris potential. Satisfactory convergence of the calculation is reached by including the Δ excitations up to 20 oscillator shells. The Δ-hole core-polarization diagrams $G_{pp\Delta h}$ are found to be very small for the sd-shell valence nucleons. A paper describing our results is being prepared for publication.

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j. Off-Shell Effects for the Reaction pp → πd at High Energies (T.-S. H. Lee, M. P. Locher,* Y. Lu,* M. Batnic,† and A. Svarc†)

The reaction pp → πd is studied in a relativistic meson rescattering model. For $1.3 < T_p < 2.4$ GeV, the differential cross section and the asymmetry are calculated and compared to experiment. The model introduces simple form factors for the leading πN partial waves, which depend on the virtuality of the exchanged π and ρ mesons. All remaining input is derived from experimental constraints. The data can be described by energy-independent form factors. The asymmetries are sensitive to pp distortion factors and further details of the model. A paper describing our results was published.

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k. Dynamical Chiral Symmetry Breaking and Confinement with an Infrared-Vanishing Gluon Propagator (C. D. Roberts, F. T. Hawes,* and A. G. Williams†)

We have studied a model Dyson-Schwinger equation for the quark propagator, constructed using an Ansatz for the gluon propagator of the form $D(q) \sim q^2/[(q^2)^2 + b^4]$ and two Ansätze for the quark-gluon vertex: the minimal Ball-Chiu and the modified form suggested by Curtis and Pennington. The aim was to determine whether such a form of the gluon propagator, which was suggested by a number of authors and which recent lattice simulations of QCD suggest may be plausible, can support dynamical chiral symmetry breaking and ensure quark confinement. The form of the gluon propagator at small space-like momenta is crucial to the nature of the strong

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interaction spectrum but is presently unknown and information gathered in such studies is invaluable in supporting or invalidating given hypotheses. It was found that there is a critical value of $b = b_c$ such that the model does not support dynamical chiral symmetry breaking for $b > b_c$. Further, it was shown that this form of gluon propagator cannot confine quarks. As a consequence this form represents a physically unreasonable model. A paper describing this work appeared in Phys. Rev. D 49, 4683-4693. In addition, these results formed the basis for an invited presentation at a workshop on quantum infrared physics and will be published in the proceedings.

ℓ. ρ–ω Mixing Self-Energy and Model Quark-Gluon Dynamics (C. D. Roberts, K. L. Mitchell,* P. C. Tandy,* and R. T. Cahill†)

The u-d quark-loop vacuum polarization process that mixes the ω and ρ mesons and its contribution to the Charge-Symmetry-Breaking (CSB) piece of the nucleon-nucleon (NN) interaction has been studied in a QCD-based, model field theory: the Global Color-symmetry Model (GCM), using a confining quark propagator obtained in earlier studies. In fitting NN phase shifts it was found necessary to include a term in the NN potential that has, conventionally, been 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 was modeled and assumed to be momentum independent. It is important to understand this term in the context of QCD. The results of this study indicate that the modification of the meson propagators produced by the quark loop is alone not sufficient to account for the observed charge symmetry breaking effects in the NN interaction. A paper describing this work appeared in Phys. Lett B335, 282-288 (1994). We are exploring other possible mechanisms which may describe the origin of CSB in the NN interaction.

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m. Dyson-Schwinger Equations and their Application to Hadronic Physics (C. D. Roberts and A. G. Williams*)

At the invitation of the editor of "Progress in Particle and Nuclear Physics" a review article which describes the present status of the application of Dyson-Schwinger equations to nonperturbative studies of quantum electrodynamics in three and four dimensions, quantum chromodynamics and hadronic physics was written. This article was written with the aim of making this increasingly useful and efficacious nonperturbative approach accessible to a larger group of physicists and to encourage its broader application. The article appeared in Prog. Part. Nucl. Phys. 33, 475-575 (1994).

*University of Adelaide, Australia.

n. Gauge Covariant Fermion Propagator in Quenched, Chirally Symmetric Quantum Electrodynamics (C. D. Roberts, Zhihua Dong,* and H. J. Munczek*)

The chirally symmetric solution of the massless, quenched, Dyson-Schwinger equation (DSE) for the fermion propagator in three- and four-dimensional quantum electrodynamics was obtained. The DSEs are a valuable nonperturbative tool for studying field theories. In recent years a good deal of progress was made in addressing the limitations of the DSE approach in the study of Abelian gauge theories. Key to this progress is an understanding of the role of the dressed fermion/gauge-boson vertex in ensuring gauge covariance and multiplicative renormalizability of the solution of the fermion DSE. The solutions we obtain are manifestly gauge covariant and a

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general gauge covariance constraint on the fermion/gauge-boson vertex is presented, which motivates a vertex Ansatz that, for the first time, both satisfies the Ward identity when the fermion self-mass is zero and ensures gauge covariance of the fermion propagator. An article describing this work appeared in Phys. Lett B333, 536-544 (1994). This research facilitates gauge-invariant, nonperturbative studies of continuum quantum electrodynamics and has already been used by others in studies of the chiral phase transition.

o. Pion Loop Contribution to the Electromagnetic Pion Charge Radius
(C. D. Roberts, A. Bender, and R. Alkofer*)

There is a widely held misconception, based on a misrepresentation of the application of chiral perturbation theory, that the electromagnetic structure of the pion is dominated by the pion's own pion-cloud. To clarify this the Global Color-symmetry Model (GCM), was used to calculate the electromagnetic charge radius of the pion. In this calculation the contributions from the quark core and pion loop were identified and compared. It was shown explicitly that the divergence of the charge radius in the chiral limit is due solely to the pion loop and that, at the physical value of the pion mass, this loop contributes less than 15% to $\langle r_\pi^2 \rangle$; i.e. the quark core is the dominant determining characteristic for the pion. This suggests that quark-based models that fail to reproduce the m_π divergence of $\langle r_\pi^2 \rangle$ may nevertheless incorporate the dominant characteristic of the pion: its quark core. The results of this studylend further support to the contention that, away from resonances, the dominant determining characteristic of kinematic and dynamical properties of hadrons is their quark core. A paper describing this work was submitted for publication.

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p. Electromagnetic Pion Form Factor
(C. D. Roberts)

A phenomenological Dyson-Schwinger/Bethe-Salpeter equation approach to QCD, formalized in terms of a QCD-based model field theory, the Global Color-symmetry Model (GCM), was used to calculate the generalized impulse approximation contribution to the electromagnetic pion form factor at space-like q^2 on the domain [0,10] GeV^2. In effective field theories this form factor is sometimes understood as simply being due to Vector Meson Dominance (VMD) but this does not allow for a simple connection with QCD where the VMD contribution is of higher order than that of the quark core. In the GCM the pion is treated as a composite bound state of a confined quark and antiquark interacting via the exchange of colored vector-bosons. A direct study of the quark core contribution is made, using a quark propagator that manifests the large space-like-q^2 properties of QCD, parameterizes the infrared behavior and incorporates confinement. It is shown that the few parameters which characterize the infrared form of the quark propagator may be chosen so as to yield excellent agreement with the available data, as illustrated in Figure IV-3. In doing this one directly relates experimental observables to properties of QCD at small space-like-q^2. The incorporation of confinement

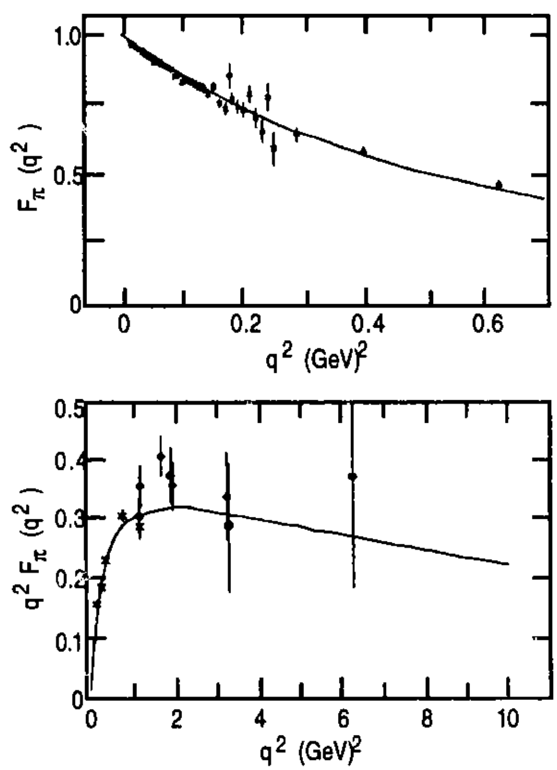

Fig. IV-3. Comparison of the calculated electromagnetic pion form factor $F_\pi(q^2)$, with available data at small space-like q^2 (upper panel) and large space-like q^2 (lower panel). Further data, in the domain $0.5 < q^2 < 5$ GeV^2, is expected from a forthcoming experiment at CEBAF.

eliminates endpoint and pinch singularities in the calculation of $F_\pi(q^2)$. With asymptotic freedom manifest in the dressed quark propagator the calculation yields $q^4F_\pi(q^2)$ = constant, up to $[q^2]$-corrections, for space-like-$q^2 \gtrsim 35$ GeV^2, which indicates that soft, nonperturbative contributions dominate the form factor at presently accessible q^2. This means that the often-used factorization Ansatz fails in this exclusive process. A paper describing this work was submitted for publication. In addition, these results formed the basis for an invited presentation at a workshop on chiral dynamics and will be published in the proceedings.

q. The Off-Shell Axial Anomaly via the $\gamma^*\pi^0 \to \gamma$ Transition (C. D. Roberts, M. R. Frank,* K. L. Mitchell,† and P. C. Tandy†)

The $\gamma^*\pi^0 \to \gamma$ form factor, $F^{\pi^0\gamma\gamma}(s)$, including the extension off the pion mass-shell, is calculated in generalized impulse approximation within the Dyson-Schwinger Equation framework used to provide an excellent description of the pion charge form factor, described above. This anomalous process is a fundamentally important characteristic of the quantum field theoretical structure of QCD because it signals the breaking of the $U_A(1)$ symmetry by quantization. This form factor was measured by the CELLO collaboration at the PETRA storage ring using the process $e^+e^- \to e^+e^-\pi^0$. There is a letter-of-intent at CEBAF to remeasure this form factor in virtual Compton scattering from a proton target. In this case a (virtual) pion is supplied by the target and a final real photon selected through the excellent missing mass spectrometry available at CEBAF. An extrapolation to the pion mass shell will be needed to deduce the physical transition form factor. Our calculation, Figure IV-4, shows that the dependence on the virtual-pion momentum is smooth and well described by a simple suppression factor, which is qualitatively independent of the details of the pion interpolating field. The correct mass-shell value of this form factor is naturally generated in our approach and the q^2 dependence is in accord with the available CELLO data (Fig. IV-4). No parameters are adjusted to achieve this; they are fixed at the values derived in the study of $F_\pi(q^2)$. A significant result of our study is that for this anomalous process, soft nonperturbative effects remain significant for $Q^2 < 20$ GeV^2. A paper describing this work was submitted for publication.

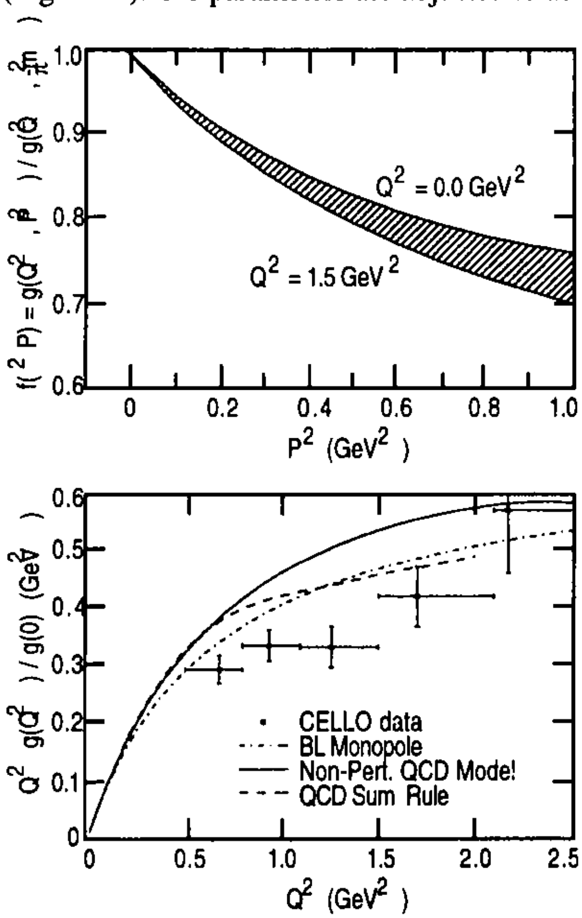

Fig. IV-4. (Upper Panel): The suppression factor for the $\gamma^*\pi^0\gamma$ transition produced by extrapolating the pion off its mass shell in the space-like direction. For any γ^* momenta between those shown, the results lie between the two curves. This illustrates that the extrapolation is smooth and well described by a simple suppression factor. (Lower Panel): The $\gamma^*\pi^0\gamma$ transition form factor at the pion mass shell. The solid line is this calculation; the dashed line is an assumed monopole shape that extrapolates the leading perturbative QCD behavior, obtained under the assumption that the amplitude factorises; and the dot-dashed line is a recent QCD sum rule calculation.

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r. Study of the Anomalous Process $\gamma\pi \to \pi\pi$ (C. D. Roberts and R. Alkofer*)

The $\gamma\pi \to \pi\pi$ form factor, $F^{3\pi}(s)$, is calculated in generalized impulse approximation within the Dyson-Schwinger Equation framework. This is an anomalous process and as such its form is a fundamentally important characteristic of the quantum field theoretical structure of QCD because it signals the breaking of the $U_A(1)$ symmetry by quantization. There is only one experimental measurement of $F^{3\pi}(s)$ at $s \sim 8m_\pi^2$, which has large errors, however, there is an approved experiment at CEBAF to study $F^{3\pi}(s)$ in the reaction $\gamma\pi^+ \to \pi^+\pi^0$ near threshold. This is to be done by measuring $\gamma p \to \pi^+\pi^0 n$ cross sections near $t \simeq -m_\pi^2$. Present calculations of $F^{3\pi}(s)$ are either unrelated to QCD or rely on "low-energy" expansions. The approach we employ, which manifestly incorporates the large space-like-q^2 renormalization group properties of QCD and allows a realistic extrapolation to small space-like-q^2, allows us to go beyond such "low-energy" expansions and relate $F^{3\pi}(s)$ to the structure of the effective quark-quark interaction in the infrared. Our preliminary results are encouraging. The chiral limit value, $F^{3\pi}(s=0)$, obtained in our approach agrees with that which one expects from the connection between anomalous processes and the quantization of QCD. Our results also indicate that the form factor grows smoothly away from the chiral point. Our detailed calculation will allow us to address the question of the reliability of the extrapolation to the pion mass shell that is necessary in interpreting the data.

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s. Electromagnetic Charged and Neutral Kaon Form Factors (C. D. Roberts, C. J. Burden,* and M. J. Thomson†)

The electromagnetic form factor of the charged and neutral kaon is calculated using the approach applied in the successful study of the pion form factor, described above. The charged kaon form factor will be measured in forthcoming experiments at CEBAF. Our calculation involves the dressed strange quark propagator, to which $F_\pi(q^2)$ is not sensitive, and hence it provides us with constraints on the strange-quark sector of QCD. Our preliminary results are encouraging. We find that the strange and up/down quark propagators are not too different, once the change in the current-quark-mass is accounted for. However, the difference that remains is important since it allows $\langle\bar{s}s\rangle<\langle\bar{u}u\rangle$. This calculation is the first to yield a value of f_K/f_π that is in good agreement with experiment and alsoyields r_{K+}/r_π in good agreement with experiment. Our calculated charged kaon form factor provides a prediction that will be tested in the forthcoming CEBAF experiments. Our studies also show that K^0 has a negative charge radius, as is to be expected. Our calculated value will be compared with that measured in K_S^0 regeneration from electrons.

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t. Bethe-Salpeter Equation Studies of $SU_f(3)$ Mesons (C. D. Roberts, C. J. Burden,* P. C. Tandy,† and M. J. Thomson‡)

The spectroscopy and weak decays of mesons composed of u, d, and s quarks is being studied using a separable approximation to the quark-quark scattering kernel. This is a first, simple step towards an extraction of the form of the quark-quark interaction at small space-like-q^2 directly from experimental observables. The kernel is obtained by using a separable approximation to invert the DSE for the quark propagator. The quark propagator used is the phenomenologically-efficacious, confining model form derived in the study of $F_\pi(q^2)$, which is described above. Preliminary results are encouraging, showing that pion observables can indeed be used as a sensitive probe of the effective quark-quark interaction in the infrared.

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u. Faddeev Equation Studies of $SU_f(3)$ Baryons Spectroscopy (C. D. Roberts, R. T. Cahill,* and P. C. Tandy†)

The spectroscopy of baryons composed of u, d and s quarks is being studied using a separable approximation to the quark-quark scattering kernel. As in the studies of mesons, the kernel is obtained by using a separable approximation to invert the DSE for the quark propagator. An initial focus of the study is to analyze the importance of diffuse diquark correlations in baryons and to determine accurately the effective mass and radius of these correlations. This Faddeev equation approach, which employs confined, dressed-quark quasi-particles, is a natural framework within which to calculate the π-N σ-term (σ_N) and preliminary results are in good agreement with the experimentally determined value. This indicates that σ_N is simply and directly related to the shift in the nucleon mass due to the nonzero bare quark masses. The approach also provides a straightforward, microscopic understanding of mass-splittings. The Faddeev amplitudes obtained will form the basis for the calculation of scattering observables such as electromagnetic form factors and Compton scattering.

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v. Electromagnetic Nucleon Form Factors (A. Bender, C. D. Roberts, M. R. Frank*)

The Dyson-Schwinger equation framework is employed to obtain expressions for the electromagnetic nucleon form factor. In generalized impulse approximation the form factor depends on the dressed quark propagator, the dressed quark-photon vertex, which is crucial to ensuring current conservation, and the nucleon Faddeev amplitude. The approach manifestly incorporates the large space-like-q^2 renormalization group properties of QCD and allows a realistic extrapolation to small space-like-q^2. This extrapolation allows one to relate experimental data to the form of the quark-quark interaction at small space-like-q^2, which is presently unknown. The approach provides a means of unifying, within a single framework, the treatment of the perturbative and nonperturbative regimes of QCD. The wealth of experimental nucleon form factor data, over a large range of q^2, ensures that this application will provide an excellent environment to test, improve and extend our approach.

*University of Washington.

w. Complex Singularities in the Quark Propagator (C. D. Roberts, and M. R. Frank*)

The Dyson-Schwinger equation for the quark propagator is being studied in the rainbow approximation using a gluon propagator that incorporates asymptotic freedom and is an entire function. The gluon propagator has a number of parameters that may be varied in order to obtain a good description of low-energy pion observables; such as f_π and the π–π scattering lengths. This provides a direct means of relating hadronic observables to the form of the quark-quark interaction in the infrared and serves as an adjunct and extension of the separable Ansatz approach discussed above. It also provides a means of examining the pole structure of the quark propagator, which may hold the key to understanding quark confinement. The preliminary results are encouraging. It was demonstrated that it is possible to obtain a good description of pion observables in this approach. Further, when the strength of the quark-quark interaction in the infrared becomes larger than a given critical value, the pole in the quark propagator bifurcates into a pair of complex conjugate poles: $m_q = m_q^R \pm i m_q^I$, which is a signal of confinement. The interpretation in this case is of $1 / m_q^I$ as the distance over which a quark may propagate before fragmenting. Further, there are indications from these studies that $T_c^D < T_c^\chi$, where T_c^D is the critical temperature for deconfinement and T_c^χ is the critical temperature for chiral symmetry restoration; i.e., indications that deconfinement occurs at a lower temperature than chiral symmetry restoration. Available results from this work will be presented at the Washington meeting of the APS.

*University of Washington.

x. Theory of Hadronic Nonperturbative Models (F. Coester and W. N. Polyzou*)

As more data probing hadron structure become available hadron models based on nonperturbative relativistic dynamics will be increasingly important for their interpretation. Relativistic Hamiltonian dynamics of few-body systems (constituent-quark models) and many-body systems (parton models) provides a precisely defined approach and a useful phenomenology. However such models lack a quantitative foundation in quantum field theory. The specification of a quantum field theory by a Euclidean action provides a basis for the construction of nonperturbative models designed to maintain essential features of the field theory. For finite systems it is possible to satisfy axioms which guarantee the existence of a Hilbert space with a unitary representation of the Póincare group and the spectral condition which ensures that the spectrum of the four-momentum operator is in the forward light cone. The separate axiom which guarantees locality of the field operators can be weakened for the construction for few-body models. In this context we are investigating algebraic and analytic properties of model Schwinger functions. This approach promises insight into the relations between hadronic models based on relativistic Hamiltonian dynamics on one hand and Bethe-Salpeter Green's-function equations on the other.

y. Current Operators in Relativistic Few-Body Systems (F. Coester, W. H. Klink,* and W. N. Polyzou*)

The interpretation of experiments that explore hadron structure with electromagnetic probes requires both a nonperturbative representation of the hadron states and a compatible representation of the current-density operator. Intuitive interpretations depend strongly on the "impulse approximation", that is, the use of one-body currents. One-body currents, however, cannot satisfy essentially the constraints imposed by the dynamics. In nonrelativistic quantum mechanics the problem of constructing dynamically required interaction currents is well understood and has been solved. Since Galilei transformations are kinematic, only time-translation covariance and current conservation impose dynamical constraints on current operators. These constraints can be satisfied by the well-known construction of so-called "minimal" or "model-independent" currents. Descriptions of hadron structure and of nuclear effects probed at high energies require a relativistic description. In relativistic few-body dynamics, one-body currents are covariant only under the kinematic subgroup of the Póincare group. Full Póincare covariance and current conservation implies dynamically determined interaction currents. The separation of the current operator into impulse current and interaction current depends on the "form of dynamics", that is on the choice of the kinematic subgroup. The choice of the light-front kinematics has unique advantages not available with other forms of dynamics: (i.) a relevant subgroup of the translations is kinematic, (ii.) initial and final states are related by kinematic Lorentz transformations, (iii.) the contributions of the individual constituents are related kinematically to the total current. These features were exploited successfully in calculations of deuteron form factors and quark-model form factors of hadrons. In these applications dynamically required interaction currents are defined implicitly by the assumption that they do not contribute to certain kinematically independent standard matrix elements. Since there are more kinematically independent matrix elements than form factors the choice of a standard subset implies an arbitrariness in the determination of "minimal" interaction currents. Our investigations were motivated by the belief that the principles involved in the current construction should not be restricted to particular elastic transitions. It should not be necessary to invent new rules for each transition of interest. The same construction should apply to all combinations of initial and final states. Elastic form factors for spin-1/2, and 1 are usually defined as invariants multiplying explicitly Lorentz covariant spinor or tensor expressions. We find that such spinor representations of the current kernels obtain for states with arbitrary spin. The key to this construction is found in the spinor representations of the subgroup O(1,2) that leaves the space-like four-momentum transfer invariant. This representation of the current kernel is related to the light-front spin representation by representations of light-front boosts in which the role of the dynamics can be isolated. A paper for publication is in preparation.

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*University of Iowa.

z. Topological Effects in Quantum Mechanics (M. Peshkin and H. J. Lipkin*)

We completed our analysis of experiments, some completed, some planned, and some only conceptual at present, that purport to demonstrate new kinds of non-local and topological effects in the interaction of a neutron with an external electromagnetic field. In the Aharonov-Casher effect (AC), the neutron interacts with an electric field and in the Scalar Aharonov-Bohm effect (SAB) the neutron interacts with a magnetic field. In both cases, the geometry can be arranged so that there is no force on the neutron but an interference experiment nevertheless finds a phase shift proportional to the applied field and to the neutron's magnetic moment.

Previously, we showed that the accepted interpretation of these phenomena as topological effects due to a non-local interaction between the neutron and the electromagnetic field is incorrect. Both AC and SAB follow from local torques on the neutron whose expectation values vanish at every instant but which have non-vanishing effect on the measurable spin-correlation variables $S(t) = (1/2) [\sigma_x(0)\sigma_x(t) + \sigma_y(0)\sigma_y(t) + h.c.]$ and $V(t) = [\sigma_x(0)\sigma_y(t) - \sigma_y(0)\sigma_x(t) + h.c.]$. We have now completed this work by observing that a criterion often used for identifying a topological effect, energy independence of the phase shift between two arms of an interferometer, is only a necessary condition, and by describing a phase shifter which obeys the energy-independence condition but whose interaction with the neutron is neither topological nor even non-local. This work was accepted for publication in Phys. Rev. Lett.

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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, computationally-intensive studies are essential parts of this program.

A new nucleon-nucleon potential, Argonne v_{18}, was completed this year. It includes a charge-independent piece similar to the older Argonne v_{14} model, plus additional charge-dependent and charge-asymmetric terms. It fits the latest pp and np elastic scattering data with a χ^2 of only 1.09/degree of freedom, as well as low-energy nn scattering parameters and deuteron properties. We also constructed a consistent set of electromagnetic transition operators and a three-nucleon potential to be used in conjunction with the v_{18} model that gives the correct ^3H and ^4He binding energies in exact calculations.

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.

Because minimization of the ground state energy is the key to determining the wave function, much of our past work was devoted to evaluating binding energies and searching for improvements in the variational wave functions. Energies in ^3H and ^4He that are ~2% above the values from available exact methods were achieved. A very significant development the last two years was the conversion of our few-body and light-nuclei programs to run on Argonne's new 128-processor IBM SP at speeds up to 7.5 GFLOPS. This has made possible extensive calculations of the $A = 6$ nuclei, five-body cluster contributions to ^{16}O, and the first extensive studies of ^{40}Ca.
The few-body trial functions were used as input to six-body Green's function Monte Carlo (GFMC) calculations in collaboration with researchers at Urbana and Los Alamos. These are the first exact calculations of six-body nuclei with realistic interactions.

In addition to ground-state calculations, we made extensive studies of the excitation spectrum of ^6He and ^6Li, using both variational and GFMC methods. We also used the charge-independence-breaking terms of the new Argonne v_{18} interaction to study the energy differences of mirror $T = 1/2$ nuclei, i.e., the Nolen-Schiffer anomaly. We continued work on ^{16}O (e,e'p) reactions. We began a study of neutron drops which can be used as a guide to the construction of Skyrme interactions for modeling neutron-rich nuclei in the crusts of neutron stars. Finally, work on hypernuclei is also continuing.

a. An Accurate Nucleon-Nucleon Potential with Charge-Independence Breaking
(R. B. Wiringa, V. G. J. Stoks*, and R. Schiavilla†)

We constructed a new accurate NN potential, designated Argonne v_{18}, with explicit charge-independence breaking. It supersedes our older v_{14} model, which was our standard nonrelativistic NN potential for most of the last decade. The main part of the new potential is charge-independent, like the old v_{14} model, with 14 components, each consisting of a radial function $v_p(r_{12})$ multiplied by an operator: 1, $\sigma_1 \cdot \sigma_2$, S_{12}, $\mathbf{L \cdot S}$, L^2, $L^2 \sigma_1 \cdot \sigma_2$, and $(\mathbf{L \cdot S})^2$, and each of these times $\tau_1 \cdot \tau_2$. Three charge-dependent and one charge-asymmetric operators are added along

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with a complete electromagnetic interaction, resulting in a model that fits pp, np, and nn data simultaneously.

The charge-dependent operators are obtained by multiplying the spin operators 1, $\sigma_1 \cdot \sigma_2$, and S_{12} by the isotensor $T_{12} = 3\tau_{1z}\tau_{2z} - \tau_1 \cdot \tau_2$, which differentiates between np and pp or nn T = 1 states. A major source of charge dependence in NN interactions is the mass difference of the charged and neutral pions, which is carefully treated in the new model. The charge-asymmetric operator is $\tau_{1z}+\tau_{2z}$ which splits pp and nn states; it is constrained by the difference between nn and pp scattering lengths. The electromagnetic interaction includes Coulomb, Darwin-Foldy, vacuum polarization, and magnetic moment terms.

The potential was fit directly to the Nijmegen pp and np scattering database as well as the nn scattering length and deuteron binding energy. With ~40 adjustable parameters it gives an excellent χ^2/degree of freedom of 1.09 for 4301 pp and np data in the range 0-350 MeV. A consistent set of two-body charge and current operators has also been derived to evaluate the deuteron electromagnetic form factors and moments. A paper on the new potential was published in Phys. Rev. C 51, 38 (1995), and the potential is already being used in calculations of few-body nuclei (Sec.B.b), ^{16}O and ^{40}Ca (Sec.B.d), and nuclear matter (Sec. B.g).

b. Variational and Green's Function Monte Carlo Calculations of Few-Body Nuclei (R. B. Wiringa, J. Carlson,* V. R. Pandharipande,† and B. S. Pudliner†)

We performed an extensive series of variational Monte Carlo (VMC) and Green's Function Monte Carlo (GFMC) calculations for few-body nuclei using a Hamiltonian, H, containing the new Argonne v_{18} NN interaction (Sec. B.a) supplemented by a model three-nucleon (3N) potential. These calculations include the ground state binding energy of ^3H, ^3He, ^4He, ^6He, ^6Li and ^6Be, low-lying excited states in the A = 6 nuclei, and scattering states of ^5He. The variational wave functions, $\Psi_v(\mathbf{R})$, include central, spin, isospin, tensor, and spin-orbit two- and three-body correlations. These trial functions give upper bounds to the ground-state binding energy ~2% above exact GFMC calculations in ^3H and ^4He.

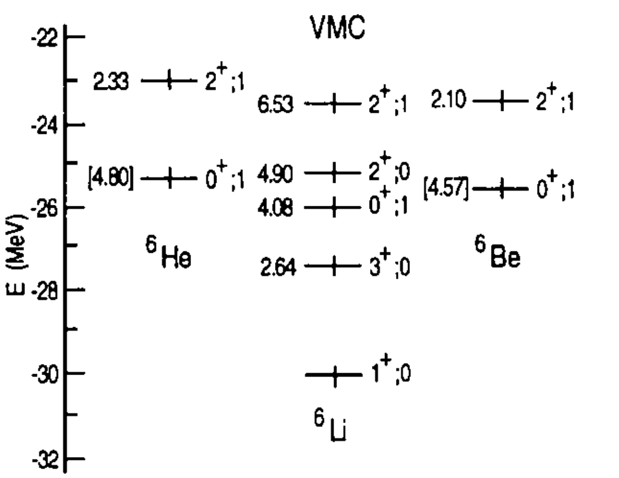

Fig. IV-5. Energy spectrum for the A = 6 nuclei from a VMC calculation using the new Argonne v_{18} NN potential and a model NNN potential. Energies are shown relative to $3*(m_n+m_p)$.

The $\Psi_v(\mathbf{R})$, serve as input to the GFMC calculations, which are made for a somewhat simplified version of the Hamiltonian, H', which omits potential terms quadratic in **L** and charge-independence-breaking (CIB) terms. The GFMC algorithm produces values of $\Psi(\tau,\mathbf{R}) = \exp(-H'\tau)\Psi_v(\mathbf{R})$ at configurations $\mathbf{R}(\tau)$ distributed with probability $|\Psi_v^\dagger(\mathbf{R})\Psi(\tau,\mathbf{R})|$. The $\exp(-H'\tau)$ is considered as a product of many small imaginary time steps $\exp(-H'\Delta\tau)$ with $\Delta\tau = 0.0001$ MeV^{-1}. The present calculations have proceeded to $\tau = 0.06$ MeV^{-1}. The transient estimate for the energy, $E(\tau)$, is well converged for A=3,4, but is still dropping for A=6 nuclei. The correction H–H' is computed by perturbation and is small.

For the full H, when the 3N potential is adjusted to give the correct A=3,4 ground state energies, we find a GFMC upper bound for the ground state of ^6Li of -31.1 ± 0.4 MeV, which is stable against α–d breakup. We estimate the converged result to be -32.4 ± 0.9 MeV, in reasonable agreement with the experimental value of -32.0 MeV.

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However, our first result for ^{6}He is not stable against α–n–n breakup. We find the correct order for excited states in ^{6}Li: (J^π;T) = (3^+;0), (0^+;1), (2^+;0), and (2^+;1), but the excitation energies are ~25% too large on average. A VMC test calculation of the A = 6 spectrum with a new 3N potential is shown in Figure IV-5.

We also studied the mass differences shown in Table IV-1 in the isospin multiplets ^{3}H–^{3}He and ^{6}He–^{6}Li–^{6}Be using the CIB terms and complete electromagnetic interaction of the Argonne v_{18} potential. We find the A=3 splitting to be 757 keV, in good agreement with the experimental 764 keV, as is the isovector A = 6 splitting. However, the isotensor A = 6 splitting has a significant problem. This discrepancy, along with details of the spectrum, may point to inadequacies in our (rather simple) 3N potential model, and may provide useful constraints for future work.

TABLE IV-1. Variational Monte Carlo calculation of energy differences (in MeV) within isospin multiplets; numbers in parentheses are Monte Carlo sampling errors.

	^{3}He - ^{3}H	^{6}Be - ^{6}He	1/2(^{6}Be+^{6}He) - ^{6}Li
$\langle v_{em} \rangle$	0.677	2.21	0.26
$\langle T_{csb} \rangle$	0.014	0.033	0
$\langle v_{csb} \rangle$	0.066	0.095	0
$\langle V_{cib} \rangle$	0	0	0.32
Δ(Calc.)	0.757(1)	2.34(2)	0.58(3)
Δ(Expt.)	0.764	2.35	0.34

The A=6 VMC and GFMC calculations were made possible by the new 128-processor IBM SP parallel supercomputer in Argonne's MCS Division, on which we have achieved speeds of up to 6 GFLOPS. A letter on this work was published in Phys. Rev. Lett. 74, 4396 (1995).

c. Improved Variational Wave Functions for Few-Body Nuclei (R. B. Wiringa, A. Arriaga,* and V. R. Pandharipande†)

We continued to work on improvements to our variational wave functions for use in Monte Carlo calculations of few-body nuclei. These trial functions include central, spin, isospin, tensor, and spin-orbit two-body correlations and three-body correlations for the three-nucleon potential. In the last two years we studied a variety of extra three-body correlations. Our search for possible forms was guided by comparisons made with 34-channel Faddeev wave functions provided by the Los Alamos–Iowa group. The new trial functions reduce the discrepancy with exact Faddeev calculations in ^{3}H and Green's Function Monte Carlo (GFMC) calculations in ^{4}He by about 40%. This work is now being written up for publication. We hope to use similar comparisons with GFMC calculations in the six-body nuclei (Sec. I.B.b) to find further improvements for the light p-shell nuclei, where the variational wave functions are not as good.

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

The methods (Sec. I.B.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 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 of form 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

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requires the evaluation of 3A-dimensional integrals which are done with Monte Carlo techniques. Most of our effort was on ^{16}O, other p-shell nuclei, and ^{40}Ca.

In 1993 the Mathematics and Computer Science Division acquired a 128-processor IBM SP which has a theoretical peak speed of 16 Gigaflops (GFLOPS). We converted our program to run on this machine. Because of the large memory on each node of the SP, it was easy to convert the program to parallel form with very low communication overhead. Considerably more effort was needed to restructure the program from one oriented towards long vectors for the Cray computers at NERSC to one that makes efficient use of the cache of the RS6000 architecture. This reprogramming was done in several stages; at present the program runs at 60 MFLOPS on a single processor or 7.5 GFLOPS on the whole machine, which we believe to be the best speed measured on the Argonne SP.

The SP made possible complete five-body cluster calculations of ^{16}O for the first time; previously we could only do four-body cluster calculations. These calculations show that the expectation value of the two-body potential is converging less rapidly than we had thought, while that of the three-body potential is more rapidly convergent; the net result is no significant change to our predicted binding energy for ^{16}O using the new Argonne v_{18} potential and the Urbana IX three-nucleon potential. This result is in good agreement with experiment.

We are also now able to do extensive four-body cluster, and partial five-body cluster, calculations of ^{40}Ca. These results are still being analyzed but our preliminary results are that ^{40}Ca is significantly underbound with this Hamiltonian. We plan to write up the ^{16}O and ^{40}Ca calculations for publication.

e. **Nolen-Schiffer Anomaly** (S. C. Pieper and R. B. Wiringa)

The Argonne v_{18} potential contains a detailed treatment of the pp, pn and nn electromagnetic potential, including Coulomb, vacuum polarization, Darwin Foldy and magnetic moment terms, all with suitable form factors and was fit to pp and pn data using the appropriate nuclear masses. In addition, it contains a nuclear charge-symmetry breaking (CSB) term adjusted to reproduce the difference in the experimental pp and nn scattering lengths. We have used these potential terms to compute differences in the binding energies of mirror isospin-1/2 nuclei (Nolen-Schiffer [NS] anomaly). Variational Monte Carlo (Sec. I.B.b.) calculations for the ^{3}He-^{3}H system and cluster variational Monte Carlo (Sec. I.B.d.) for the ^{15}O-^{15}N and ^{17}F-^{17}O systems were made. In the first case, the best variational wave function for the A = 3 nuclei was used. However, because our ^{16}O wave function does not reproduce accurately the ^{16}O rms radius, to which the NS anomaly is very sensitive, we adjusted the A = 15 and A = 17 wave functions to reproduce the experimental density profiles.

Our computed energy differences for these three systems are $0.757 \pm .001$, $3.544 \pm .018$ and $3.458 \pm .040$ MeV respectively, which are to be compared with the experimental differences of 0.764, 3.537, and 3.544 MeV. Most of the theoretical uncertainties are due to uncertainties in the experimental rms radii. The nuclear CSB potential contributes 0.066, 0.188, and 0.090 MeV to these totals. We also attempted calculations for A = 39 and A = 41. However, in these cases, the experimental uncertainties in the rms radius make it impossible to extract useful information about the contribution of the nuclear CSB potential.

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

We have used our ^{16}O Monte Carlo program to compute the $p_{3/2}$ quasihole wave function in ^{16}O and the Pavia program to compute $^{16}O(e,e'p)$ $^{15}N(3/2^-)$ with this wave function. We also developed a local-density approximation (LDA) for obtaining the quasihole wave function from a mean-field wave function, and studied the effects of using this LDA on the outgoing distorted waves. We find that we can predict correctly the contribution of the interior of the nucleus to the observed (e,e'p) cross sections, but the surface contribution is too large. The LDA modifications to the outgoing wave function are small. This work was published.

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g. Nuclear and Neutron Matter Studies (R. B. Wiringa, A. Akmal,* and V. R. Pandharipande*)

We are studying nuclear and neutron matter with the new Argonne v_{18} NN and Urbana 3N potentials. We use variational wave functions and a diagrammatic cluster expansion with Fermi hypernetted and single-operator chain (FHNC/SOC) integral equations to evaluate the energy expectation value. Initial results show some interesting differences with our previous calculations with the older Argonne v_{14} potential. In particular, there are a number of diagrams involving $\mathbf{L{\cdot}S}$ and L^2 terms which were small with the older model and were rather crudely estimated or even neglected. It appears that these terms are more important with the new potential and will have to be evaluated more accurately. Work on this subject is in progress. A simple line of attack is to just add additional diagrams at the three-body cluster level. A longer term approach may be to adapt some of the methods for evaluating nucleon clusters used in the few-body and closed shell nuclei described above (Secs. B.b and B.d).

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h. Elementary Diagrams in Nuclear and Neutron Matter (R. B. Wiringa)

Variational calculations of nuclear and neutron matter are currently performed using a diagrammatic cluster expansion with the aid of nonlinear integral equations for evaluating expectation values. These are the Fermi hypernetted chain (FHNC) and single-operator chain (SOC) equations, which are a way of doing partial diagram summations to infinite order. A more complete summation can be made by adding elementary diagrams to the procedure. The simplest elementary diagrams appear at the four-body cluster level; there is one such E_4 diagram in Bose systems, but 35 diagrams in Fermi systems, which gives a level of approximation called FHNC/4. We developed a novel technique for evaluating these diagrams, by computing and storing 6 three-point functions, $S_{xyz}(r_{12}, r_{13}, r_{23})$, where xyz (= ccd, cce, ddd, dde, dee, or eee) denotes the exchange character at the vertices 1, 2, and 3. All 35 Fermi E_4 diagrams can be constructed from these 6 functions and other two point functions that are already calculated.

The elementary diagrams are known to be important in some systems like liquid ^3He. We expect them to be small in nuclear matter at normal density, but they might become significant at higher densities appropriate for neutron star calculations. This year we programmed the FHNC/4 contributions to the energy and tested them in a number of simple model cases, including liquid ^3He and Bethe's homework problem. We get reasonable, but not exact agreement with earlier published work. In nuclear and neutron matter with the Argonne v_{14} interaction these contributions are indeed small corrections at normal density and grow to only 5-10 MeV/nucleon at 5 times normal density.

The same method can also be used to construct some elementary single-operator chain diagrams, at the SOC/4 level. These corrections are probably also small, but might make some contribution in high-density matter. Work on these terms is now in progress.

i. Spin-Orbit Splitting in Neutron Drops (S. C. Pieper, V. R. Pandharipande,* and D. G. Ravenhall*)

Hartree-Fock calculations of very neutron-rich nuclei are an essential source of input for calculations of the properties of neutron-star crusts. The Hartree-Fock calculations often use Skyrme models whose parameters are determined by fits to known (hence not neutron-rich) nuclei and extrapolations to the N >> Z case. The Vautherin and Brink (VB) prescription for the isospin dependence of the spin-orbit potential, V_{so}, is usually used; this is based on the assumption that most of V_{so} comes from a short-range $L \cdot S$ nucleon-nucleon interaction.

In 1993 we showed that more than half of the spin-orbit splitting in ^{15}N comes from long-range three-nucleon potentials and correlations, which violate the VB assumption. To investigate the isospin dependence of the spin-orbit splitting, we made calculations of the type described in Sec. B.d for systems of 7 (p-wave splitting) and 19 (d-wave) neutrons. The neutrons were confined in external potentials that were adjusted to give physically reasonable densities. We find that the spin-orbit splitting of these drops is less than half the ^{15}N value. These values can be used to determine an isospin dependence of V_{so} that is very different from that of VB. Hartree-Fock calculations of known spin-orbit splittings in nuclei with N significantly different from Z are now being made with this new prescription.

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j. Ground State of Hypernuclei (S. C. Pieper, A. Usmani,* and Q. N. Usmani†)

The cluster variational Monte Carlo calculation of nuclei (Sec. B.d) was adapted for hypernuclei such as $^{17}_{\Lambda}O$, $^{16}_{\Lambda}O$, $^{12}_{\Lambda}C$. In this calculation we use the same realistic nuclear Hamiltonians that 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 is also of the same form as in normal nuclei with additional NΛ and NNΛ non-central correlations.

The development work for these calculations was done principally by A. Usmani and Q. N. Usmani at Jamia Millia. Final production calculations were done on the NERSC computers.

During the summer of 1994, an article describing this work was written while S. C. Pieper was a visitor at Trieste, Italy, where A. Usmani is a postdoctoral research fellow. Travel and living expenses for S. C. Pieper to visit Jamia Millia and Q. N. Usmani to visit ANL, were provided by a NSF grant; the visit to Trieste was paid for by SISSA.

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

We are continuing our work on the Λ hyperon single-particle (s.p.) energies and their interpretation in terms of the basic Λ-nuclear interactions. In particular we are interpreting the results obtained by S. C. Pieper, A. Usmani and Q. N. Usmani (Sec. B.j). We obtain about 30 MeV for the repulsive contribution of the three-body ΛNN forces in nuclear matter. We are able to exclude purely "dispersive" ΛNN forces. We are investigating the mix of dispersive and two-pion-exchange ΛNN forces which provide a fit to the s.p. data. For interactions, which provide a fit to the s.p. data, the Λ binding energy as a function of the nuclear matter density shows characteristic

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saturation features with a maximum at a density not very different from that of normal nuclear matter. We obtain a more precise measure of the space-exchange part of the Λ-nuclear force than was previously available, corresponding to an exchange parameter ≃ 0.32. The space-exchange force is rather directly related to the effective mass of a Λ in the nuclear medium and turns out to be about 70% of its free mass. As a result, we also obtain a much better value for the p-state Λ-nucleus potential which is about 40% of the s-state potential. The Λ binding to nuclear matter is determined to be ≃ 28 MeV.

ℓ. **Core-Nucleus Distortion in Hypernuclei** (A. R. Bodmer and Q. N. Usmani*)

We are completing a study of the effects of the spherical distortion of the "core" nucleus by the Λ in a hypernucleus. The response of the core was determined by an appropriately chosen energy-density functional which depends, in particular, on the nuclear compressibility. The forcing action of the Λ is determined by the nuclear density dependence of the Λ binding in nuclear matter which is obtained from our work on the Λ single-particle energies. Because of the strongly repulsive ΛNN forces, this Λ binding "saturates" at a density close to the central density of nuclei, and results in a reduced core-nucleus distortion much less than would otherwise be obtained. The effects of the core distortion then turn out to be very small even for quite light hypernuclei. This result justifies the assumption that spherical core nuclei are effectively undistorted in a hypernucleus.

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m. **Space-Exchange Effects in Light Hypernuclei** (A. R. Bodmer, M. Shoeb,* and Q. N. Usmani†)

We made variational Monte Carlo calculations of the ground-state Λ separation energies B_Λ of the s-shell hypernuclei $\left({}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H, {}^{5}_{\Lambda}He\right)$ and of ${}^{9}_{\Lambda}Be$ for interactions which include central ΛN potentials with a space-exchange component and three-body ΛNN forces. The s-shell hypernuclei are treated as A-Body systems (A = baryon number), and ${}^{9}_{\Lambda}Be$ is analyzed in a $\Lambda + 2\alpha$ model. The reduction of B_Λ due to a space-exchange ΛN potential was obtained for the s-shell hypernuclei. For ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{5}_{\Lambda}He$, the exchange energy is approximately 0.04, 0.15 and 0.5 MeV respectively. For ${}^{9}_{\Lambda}Be$ a more limited study gives about 1.3 MeV. These values are much larger than for soft potentials for which the correlations are weak. This work was submitted for publication.

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n. **Charge-Symmetry Breaking Λ-Nucleon Interaction** (A. R. Bodmer, M. Murali,* and Q. N. Usmani*)

Some time ago we showed that the charge-symmetry-breaking interaction, as obtained from the mass four hypernuclei $\left({}^{4}_{\Lambda}H, {}^{4}_{\Lambda}He\right)$, was spin-independent; a result which cannot be understood with the conventional meson-exchange models. The calculations of $\left({}^{4}_{\Lambda}H, {}^{4}_{\Lambda}He\right)$ are currently being extended to include noncentral nuclear and hypernuclear forces which could modify this result. At a more fundamental level we intend to study quark-structure contributions to the charge-symmetry-breaking interaction.

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o. Suppression of the Λ-Σ Coupling in Nuclear Matter (A. R. Bodmer and Q. N. Usmani*)

We initiated a study of the modification of the coupling of the ΛN to the ΣN channel in nuclear matter with the Fermi hypernetted-chain variational approach. This modification of the ΛN-ΣN coupling is a central problem in hypernuclear physics and is related closely to the strongly repulsive three-body forces which are needed to account for hypernuclear binding energies. All earlier calculations have only considered this problem in the so-called G-matrix approximation which neglects important higher-order effects. An important result of this work will be a better understanding of the density dependence of Λ binding in nuclear matter, which can then be tested in the calculation of the Λ single-particle energies.

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C. NUCLEAR STRUCTURE AND HEAVY-ION REACTIONS

This research focuses on nuclear structure in unusual regimes: neutron-rich nuclei far from stability, and superdeformed nuclei frequently at high spin. We also study heavy-ion reactions near the Coulomb barrier and some traditional shell model problems. Much of this work is closely tied to experiments performed at ATLAS and at radioactive-beam facilities.

Our studies of neutron-rich nuclei have focused on Coulomb dissociation as a method of extracting the dipole response in nuclei like ^{11}Li and ^{11}Be. We are also studying pairing effects in these nuclei, with applications both to the neutron-rich nuclei that are present in the crusts of neutron stars and those that will be produced in future radioactive-beam experiments.

The studies of heavy-ion 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 reactions, compound-nucleus spin distributions, elastic and inelastic scattering, and transfer reactions. The calculations are constrained by the nuclear structure of the interacting nuclei.

Our studies of superdeformed nuclei, at both low and high spins, address new regions of superdeformation, rotational moments of inertia, and the transition from superdeformed to normal states. Other areas of interest are the density-dependence of residual interactions and the structure of the heaviest elements. We try to understand these phenomena on the basis of correlations induced by the effective two-body interaction. The techniques used include a deformed one-body potential for surveying nuclear structure over a large regime, self-consistent mean-field calculations for more detailed studies of particular nuclides, and many-body wave functions when residual interactions are weak and a mean-field approach is inadequate.

Much of this work is computer intensive, and in the past year we have adapted our codes to exploit Argonne's new massively-parallel IBM SP supercomputer. This has allowed us to calculate energy surfaces using the Strutinsky method in a four-dimensional space, including quadrupole, octupole, and hexadecapole shapes and a necking degree of freedom. This technique is being used to study nuclei in the A~180 mass region, along with Hartree-Fock methods. We are also looking at rotational bands near A~150 where there is evidence for very large moments of inertia, and at identical bands near A~190, where we are trying to treat general pairing interactions. We are involved in several experiments at ATLAS searching for superdeformed and hyperdeformed nuclei.

a. Heavy-ion Reactions near the Coulomb Barrier (H. Esbensen, K. E. Rehm, C. L. Jiang, B. Crowell, J. Gehring, B. Glagola, R. Henry, M. D. Rhein, and A. H. Wuosmaa)

Fusion reactions between different Kr and Ni isotopes were measured recently at ATLAS. We performed coupled-channels calculations and made comparisons to the measurements. Such calculations become increasingly difficult for heavy, soft nuclei due to strong couplings and the importance of higher-order, multi-step processes. The calculations were made possible by adopting the so-called rotating frame approximation, and they included one- and two-phonon excitations of the low-lying 2^+ and 3^- states in both the projectile and the target.

These calculations reproduced quite accurately the measured fusion cross sections for a beam of ^{86}Kr. Some discrepancies remain for the much softer ^{78}Kr nucleus; the calculations were clearly much more sensitive to higher-order processes in this case. In particular, it was important to implement the correct coupling strength and excitation energy for the soft, one- to two-phonon quadrupole transition in ^{78}Kr, which differs significantly from the vibrational limit. This work was performed in collaboration with the experimentalists and was submitted for publication.

We also performed-coupled channels calculations for multineutron transfer reactions between different Ni and Mo isotopes. The measurements of these reactions, which were performed recently at ATLAS, cannot be reproduced by a successive one-neutron transfer mechanism. The data can, however, be reproduced fairly well by including a direct pair-transfer coupling. We hope to achieve a consistent description of the observed fusion, transfer and elastic scattering data. This work is in progress.

b. Higher-order Dynamical Effects in Coulomb Dissociation (H. Esbensen, G. F. Bertsch,* and C. A. Bertulani†)

Coulomb dissociation is a technique commonly used to extract the dipole response of nuclei far from stability. This technique is applicable if the dissociation is dominated by dipole transitions and if first-order perturbation theory is valid. In order to assess the significance of higher-order processes we solve numerically the time evolution of the wave function for a two-body breakup in the Coulomb field from a high Z target. We applied this method to the breakup reactions: $^{11}Be \rightarrow {}^{10}Be + n$ and $^{11}Li \rightarrow {}^{9}Li + 2n$. The latter is treated as a two-body breakup, using a di-neutron model.

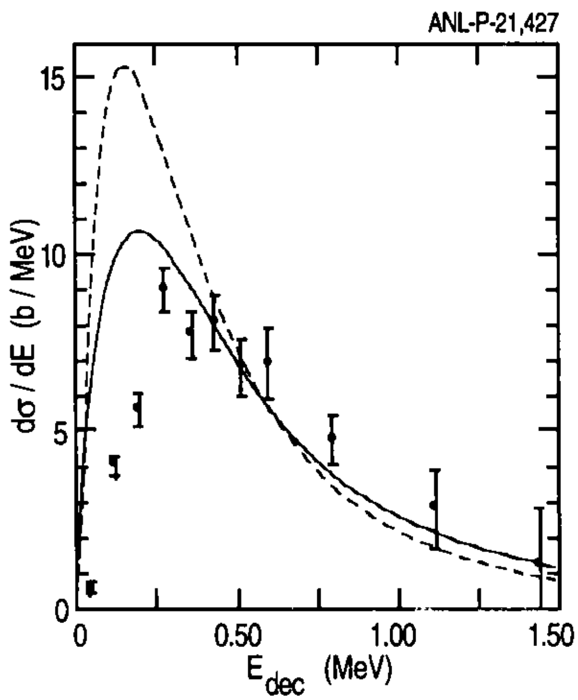

Fig. IV-6. Decay energy spectrum of ^{11}Li after Coulomb dissociation on a lead target at 28 MeV/A, obtained from first-order perturbation theory (dashed curve), from higher-order dynamical calculations (solid curve), and from experiment [D. Sackett et al., Phys. Rev. C 48, 118 (1993)].

We find that the breakup cross section can be determined quite reliably from first-order perturbation theory. The decay energy spectrum, on the other hand, is distorted at 28 MeV/u, where the ^{11}Li breakup was measured; the peak-height is significantly reduced compared to first-order perturbation theory, and the tail at higher excitation energies is slightly enhanced. This is shown in Figure IV-6. The effect of higher-order processes is much smaller at 72 MeV/u, where the ^{11}Be breakup was measured.

A clear signature of the influence of higher-order processes was observed in the momentum distributions for the relative motion of the two fragments: the transverse momentum distribution (in the scattering plane) becomes asymmetric, and charged fragments acquire a larger, average longitudinal momentum than the neutral neutron fragments. The influence of higher-order processes can easily be reduced simply by performing the dissociation experiment at a higher beam energy. This work was published in Nucl. Phys. A581, 107 (1995).

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c. Coulomb Excitation of C_{60} Molecules (H. Esbensen, H. G. Berry, S. Cheng, R. W. Dunford, D. S. Gemmell, E. P. Kanter, T. LeBrun, and W. Bauer*)

The ionization and dissociation of C_{60} molecules in the Coulomb field from fast, highly-charged xenon ions was measured recently at ATLAS. The Coulomb excitation was modeled as a coherent excitation of the giant plasmon resonance. Guided by photo-absorption measurements, single-plasmon excitations were identified with the production of single-charged C_{60}^{+} molecular ions. The calculated cross sections do indeed reproduce the beam energy-dependence of the measured C_{60}^{+} yield. The calculations show that single-plasmon excitations are responsible for about half of the total reaction cross section. The other half, i.e., multiplasmon excitations, leads to multiple ionization and dissociation of the molecule. This work was published together with the experimental work in Phys. Rev. Lett. 72, 3965 (1994).

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d. Positive Parity States in ^{11}Be (H. Esbensen, H. Sagawa,* and B. A. Brown†)

A good example of a nucleus which contains a one-neutron halo is ^{11}Be, and many different measurements of the $^{11}Be \rightarrow {}^{10}Be + n$ breakup reaction were performed in recent years. These measurements are often compared to predictions of simple single-particle models for the valence neutron. In order to obtain a more realistic description, we calculated the ground state and the low-lying, positive parity states of ^{11}Be in a particle-rotor model, making use of a quadrupole, neutron-core coupling that is consistent with the known B(E2)-value.

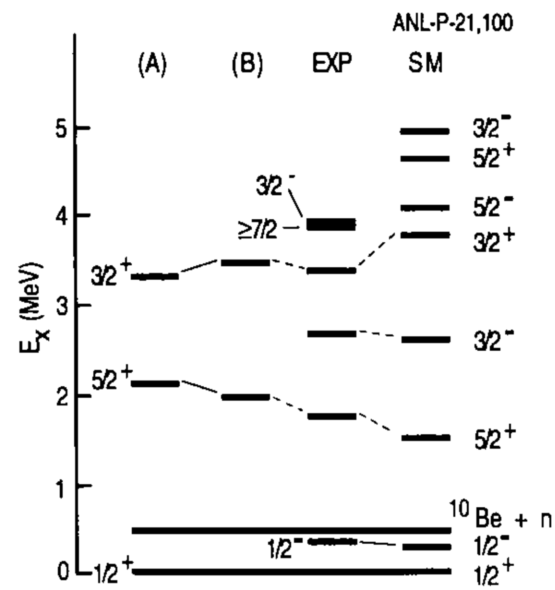

Fig. IV-7. Energy spectra of ^{11}Be, obtained from measurements (EXP) and shell-model calculations (SM). The positive-parity states we obtain from our particle-rotor model is shown in column (A). Column (B) shows the result we obtain by reducing the 2^+ quadrupole moment of the core to 1/3 of the perfect rotor limit.

Our model describes the low-lying positive parity states rather well. This is illustrated in Figure IV-7. The ground-state wave function that we obtain consists mainly of an $s_{1/2}$ single-particle state coupled to the 0^+ ground state of the core (87%). This is in reasonable agreement with shell-model predictions and with the measured spectroscopic factor. The large s-wave content of the ground state implies a very large rms radius for the valence neutron, and the calculated matter distribution agrees very well with the one extracted from fragmentation data.

Shell-model calculations indicate that ^{10}Be is not a perfect rotor; the predicted quadrupole moment of the lowest 2+ state is only one third of the value extracted from the measured B(E2) value. Repeating our calculations with the reduced 2^+-2^+ coupling strength we obtain an even better agreement with the measured positive-parity spectrum of ^{11}Be. This work was published in Phys. Rev. C (March 1995).

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e. **Pairing Gap in the Inner Crust of Neutron Stars** (H. Esbensen, R. A. Broglia,* E. Vigezzi,* and F. Barranco†)

The pairing gap in the inner crust of a neutron star can be strongly affected by the presence of heavy nuclei. The effect is commonly estimated in a semiclassical description, using the local density approximation. It was found that the nuclear specific heat can become comparable to the electronic specific heat at certain densities and temperatures. The quantitative result depends critically upon the magnitude of the pairing gap. We therefore decided to assess the validity of the semiclassical approach. This is done by solving the quantal BCS pairing gap equation for neutrons that are confined to the Wigner-Seitz cell that surrounds a heavy nucleus. We performed calculations that are based on the Gogny pairing force. They are feasible for realistic densities of neutrons and heavy nuclei that are expected to be found in the inner crust of neutron stars. The results will be compared to the semiclassical predictions. This work is in progress.

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f. **Pair correlations in Neutron-Rich Nuclei** (H. Esbensen)

We started a program to study the ground-state properties of heavy, neutron-rich nuclei using the Hartree-Fock-Bogolyubov (HFB) approximation. This appears at present to be the most realistic approach for heavy nuclei that contain many loosely bound valence neutrons. The two-neutron density obtained in this approach can be decomposed into two components, one associated with the mean field and one associated with the pairing field. The latter has a structure that is quite similar to the pair-density obtained by diagonalizing the Hamiltonian for a two-neutron halo, which was studied earlier. This allows comparison of the HFB solutions against numerically exact solutions for two-neutron halos. This work is in progress. We intend to apply the HFB method to predict the ground-state properties of heavier, more neutron-rich nuclei that may be produced at future radioactive beam facilities.

g. **Nuclear Energy Surfaces at High-Spin in the A~180 Mass Region** (R. R. Chasman, J. L. Egido,* and L. M. Robledo*)

We are studying nuclear energy surfaces at high spin, with an emphasis on very deformed shapes using two complementary methods: (1) the Strutinsky method for making surveys of mass regions and: (2) Hartree-Fock calculations using a Gogny interaction to study specific nuclei that appear to be particularly interesting from the Strutinsky method calculations. The great advantage of the Strutinsky method is that one can study the energy surfaces of many nuclides (~300) with a single set of calculations. Although the Hartree-Fock calculations are quite time-consuming relative to the Strutinsky calculations, they determine the shape at a minimum without being limited to a few deformation modes. We completed a study of ^{182}Os using both approaches. In our cranked Strutinsky calculations, which incorporate a necking mode deformation in addition to quadrupole and hexadecapole deformations, we found three well-separated, deep, strongly deformed minima. The first is characterized by nuclear shapes with axis ratios of 1.5:1; the second by axis ratios of 2.2:1 and the third by axis ratios of 2.9:1. We also studied this nuclide with the density-dependent Gogny interaction at I = 60 using the Hartree-Fock method and found minima characterized by shapes with axis ratios of 1.5:1 and 2.2:1. A comparison of the shapes at these minima, generated in the two calculations, shows that the necking mode of deformation is extremely useful for generating nuclear shapes at large deformation that minimize the energy. The Hartree-Fock calculations are being extended to larger deformations in order to further explore the energy surface in the region of the 2.9:1 minimum.

Until now, our Strutinsky calculations were restricted to reflection symmetric shapes because of the very large computer resources that are needed to study reflection asymmetric shapes on large

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grids in deformation space. With the recent availability of large computer resources on the SP system at Argonne, together with the continued availability of computing resources at NERSC, it is feasible to carry out Strutinsky calculations on a large four-dimensional grid in a deformation space that includes octupole deformation in addition to quadrupole, hexadecapole and necking deformations. We are carrying out this study of the A~180 region concentrating on the questions : (1) how do the inclusion of necking and reflection-asymmetric degrees of freedom modify nuclear energy surfaces; and (2) how soft are the many known, very deformed nuclear shapes in this region to octupole deformation?

We completed the first phase of these studies, using the Strutinsky method to calculate nuclear energy surfaces in the four-dimensional space discussed above. Comparing the results obtained with and without octupole deformation (see Figures IV-8 and IV-9), we found major modifications of the energy surface in many nuclei in the region around ^{176}W. These effects are strong at all values of the angular momentum. There are reductions of the total energy of ~ 7 MeV for the necked-in shapes at the largest deformations.

This feature can be understood in terms of incipient fission fragments. The reflection-asymmetric shape is necked-in in such a way as to exploit the large shell corrections associated with a strongly deformed fragment in the vicinity of ^{100}Zr and a spherical fragment in the vicinity of ^{80}Zr. The symmetric necked-in shape at these large deformations corresponds to two strongly deformed incipient fission fragments near A = 90 and is not favored. The effects are huge here, compared to typical octupole deformation energy gains of less than 1 MeV.

We looked at the softness of the known very deformed minima in this mass region. We find that, by and large, the energy increase as a function of octupole moment is roughly the same for all of the known very deformed minima in this mass region. The energy increases by ~1 MeV for octupole deformations of 0.05. The shapes characterized by axis ratios of 2.5:1 in the nuclides near ^{170}Yb are somewhat softer to octupole deformations; and those characterized by

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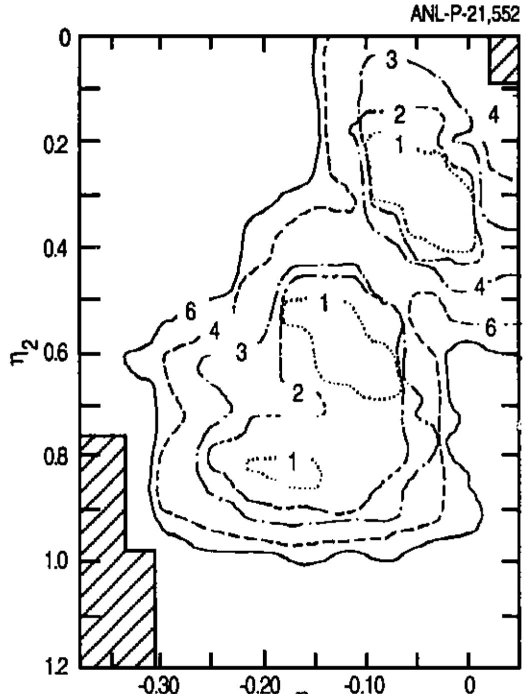

Fig. IV-8. Energy surface of ^{176}W at I = 70. Only reflection symmetric shapes are included. The numbers on the contours are excitation energy in MeV. η_2 is the necking of the shape.

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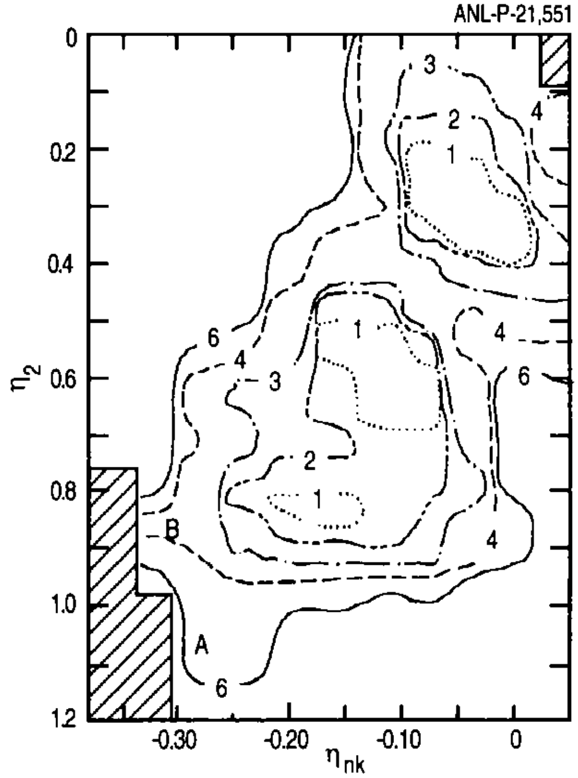

Fig. IV-9. Energy surface of 176W at I = 70. Reflection asymmetric shapes are also included in this figure. See caption for Fig. IV-8.

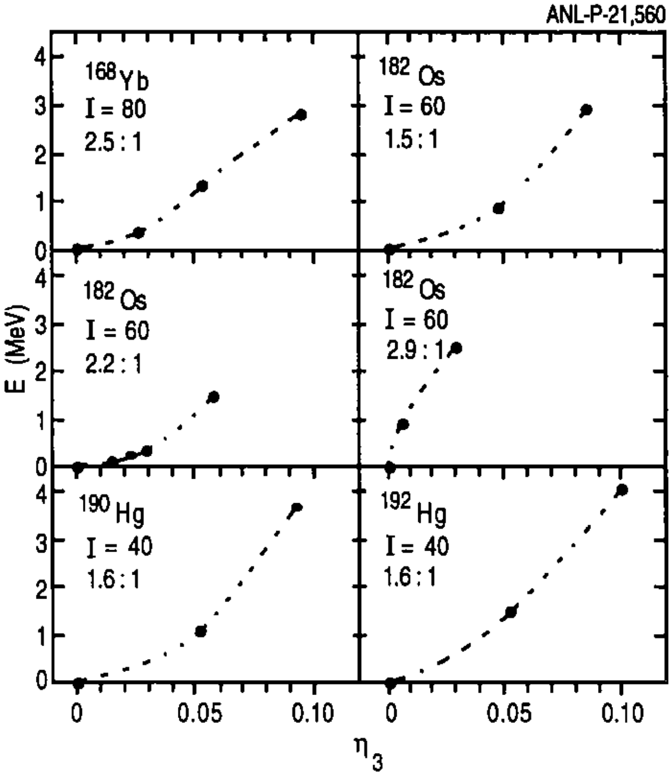

Fig. IV-10. Energy as a function of η_3 for characteristic extended minima in the A~180 region. The lines are drawin to guide the eye. η_3 is octupole deformation.

2.9:1 axis ratios in the nuclides near ^{182}Os are considerably stiffer to octupole deformations (see Figure IV-10).

As in the case for Strutinsky method calculations, the introduction of reflection-asymmetry doubles the basis space that must be used in Hartree-Fock calculations. We are in the process of extending the Hartree-Fock codes to allow us to calculate the properties of very deformed reflection asymmetric shapes at high spins. We are also extending the generator-coordinate method codes to make a microscopic study of the odd-parity excitations in the very extended minima.

h. **Very Extended Shapes in the A ~ 150 Mass Region** (R. R. Chasman)

There was a report of a rotational band in ^{152}Dy or ^{153}Dy that is characterized by a dynamic moment of inertia of $130\hbar^2$ MeV^{-1}. For purposes of orientation, it should be noted that the well known superdeformed bands in this region are characterized by moments of inertia of ~90. Some calculations were carried out in two- and three-dimensional shape spaces, in order to understand this experimental observation. These calculations show either very shallow minima and/or minima that do not become yrast below I = 90 at the very large deformations that would seem to be required to explain such a large moment of inertia. We extended our four-dimensional deformation space Strutinsky calculations to a study of this mass region, with the hope of gaining some insight into the nature of this band. We are also analyzing the other nuclides of this mass region with the hope of finding other instances of such very extended shapes. This analysis is almost complete.

i. **Rotational Spacings in Superdeformed Bands of Nuclei** (R. R. Chasman and A. Farhan*)

An unexpected result of the experimental investigation of superdeformed rotational bands is the observation of near-identical dynamic moments of inertia in different nuclei. This phenomenon was also noted in normally deformed rotational bands.

A priori, the BCS method is suspect at I = 0 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. At high spin, pairing correlations are further weakened, and the BCS method becomes even worse.

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In our studies of nuclear structure of the actinides, we found that a conventional pairing force with constant matrix elements does not do a good job of explaining low-energy spectra. A density-dependent pairing force does a considerably better job of describing these spectra. In a superdeformed nucleus, the ratio of surface to volume is much larger than it is in the case of the normally deformed actinides, and we expect density-dependent effects to play an even more important role.

The above considerations motivated us to undertake a many-body calculation of moments of inertia, going beyond the usual BCS treatment of pairing correlations in two ways: (1) we use wave functions with good particle number and; (2) we do a configuration interaction calculation. In the configuration interaction calculations, we use the proton and neutron pairing interaction strengths and the cranking frequency to generate configurations for the interaction calculation. Our many-body wave functions are products of sums of terms. Each such wave function has $\sim 10^{12}$ amplitudes, and contains ~2000 variational parameters. We minimize the variational parameters after projecting states of good particle number, good parity, and good signature.

As a first step, we carried out a calculation of rotational spacings in the superdeformed band of ^{192}Hg, using constant pairing matrix elements, to test the adequacy of conventional calculations of rotational spacings. This study shows that it is extremely important to take configuration interaction effects into account. Above I = 30, the energy can be lowered by >300 keV by including configuration interaction effects with the wave functions generated by varying the pairing interaction strengths. We get additional lowering of ~200 keV when states generated from all cranking frequencies are also included in the configuration interaction calculation. These shifts are relative to a wave function with good particle number. The shifts are even larger relative to wave functions calculated in the BCS approximation.

Using these many-body wave functions, we are now examining the effect on rotational spacing arising from changes in the pairing force matrix elements. We are developing a code to calculate pairing matrix elements for a finite-range interaction.

j. Experimental Search for Very Extended Shapes in the A~180 Region

(M. P. Carpenter, R. R. Chasman, R.V.F. Janssens, I. Ahmad, B. Crowell, R. G. Henry, T. L. Khoo, T. Lauritsen, D. Nisius)

A very important question in nuclear structure studies is the adequacy of the Strutinsky method for states at very large deformation. According to our calculations, nuclides in the vicinity of ^{182}Os are expected to have an accessible minimum that is more deformed than any minimum that has so far been populated at high spin in heavy ion reactions. Studies of this region will provide useful tests of the Strutinsky approach, and perhaps allow us to fine tune some of the ingredients of these calculations dealing with extended shapes.

A first attempt to populate this minimum in ^{182}Os was made by bombarding ^{138}Ba at the LBL 88" cyclotron with a 220 MeV ^{48}Ca beam. This produces states in ^{182}Os with angular momenta of I ~ 70. Our calculations predict that the very extended minimum (2.2:1) is yrast at this angular momentum. The shapes of nuclei associated with states in this extended minimum is quite different from that of the conventional superdeformed nuclide that bulges out at Z = 0. It is flat and one needs a necking degree of freedom in the deformation space to calculate this minimum. This search was not successful because of oxygen contamination in the target giving rise to many unwanted γ rays.

According to our calculations, it should be almost as easy to make states in the 2.2:1 minimum of ^{180}Os as it is in ^{182}Os. An experiment was approved at Gammasphere to search for the very extended minimum of ^{180}Os.

k. Single Particle States in the Heaviest Elements (I. Ahmad and R. R. Chasman)

The search for superheavy elements was 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 in the strongly deformed nuclides near A = 250. The orbitals that are important for fixing 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, e. g. the 1/2-[761] orbital was already identified in ^{251}Cf is quite sensitive to the spherical $j_{13/2}$ orbital. The position of the 1/2+[880] deformed orbital is very sensitive to the $k_{17/2}$ spherical state. According to our calculations, this state should be found at ~1500 KeV in ^{251}Cf and should be populated in a one-nucleon transfer reaction using an (α,^{3}He) reaction. We calculated signatures for the low-lying states in ^{251}Cf and the calculated energies and signatures are in good agreement with the experimentally observed (d,p) spectrum. We expect to see the high-j states in an (α,^{3}He) study. Our analysis of low-lying states in ^{251}Cf was published. The (α,^{3}He) experiment was approved, and is waiting on the preparation of a target.

ℓ. Many-Body Wave Functions (R. R. Chasman)

In the past few years, we developed many-body variational wave functions that allow one to treat pairing and particle-hole two-body interactions on an equal footing. The complexity of these wave functions depends on the number of levels included in the valence space, but does not depend on the number of nucleons in the system. By using residual interaction strengths (e.g. the quadrupole interaction strength or pairing interaction strength) as generator coordinates, one gets many different wave functions, each having a different expectation value for the relevant interaction mode. These wave functions are particularly useful when one is dealing with a situation in which the mean-field approximation is inadequate. Because the same basis states are used in the construction of the many-body wave functions, it is possible to calculate overlaps and interaction matrix elements for the many-body wave functions (which are not in general orthogonal) easily. The valence space can contain a large number of single-particle basis states, when there are constants of motion that can be used to break the levels up into groups. We added a cranking term to the many-body Hamiltonian and modified the projection procedure to get states of good signature before variation. In our present implementation, each group is limited to eight pairs of single-particle levels. We are working on ways of increasing the number of levels that can be included in each group. We are also working on including particle-particle residual interaction modes, in addition to pairing, in our Hamiltonian.

m. Anomalous Transition in ^{10}B (D. Kurath)

The transitions between the J,T = 3,0 ground state of ^{10}B and the 3,0 state at 4.77 MeV present some puzzling features. The gamma transition between the states is of unknown multipolarity and very weak, with a strength of only 0.1 WU even if it is a pure E2. The shell model with the Cohen-Kurath POT interaction predicts a nearly pure E2 transition but with a transition probability about 4 times too strong.

Recent inelastic pion scattering experiments on ^{10}B excited this state with a strength only one tenth the value predicted by the shell model. It was found that these weak transitions are very sensitive to the wave functions and that orthogonally mixing the states with an intensity of 2% can satisfy both the pion scattering and the γ decay (60% E2, 40% M1).

Very recent preliminary results of electron scattering on ^{10}B include the inelastic form factors for this transition. The indication from the maximum of the longitudinal form factor is that if it is a C2 transition it is much stronger than one would expect from the gamma and pion evidence. In addition as the momentum transfer increases it falls much more rapidly than the usual C2 shape. Therefore the possibility of a C0 monopole transition was explored.

One way a C0 transition can arise within the 1p-shell is to have a larger mean-square radius for the $p_{1/2}$ orbit than for the $p_{3/2}$ orbit. The result was calculated assuming a value of 0.2 fm for this difference. The transition is very weak although it has nearly the experimental shape. Even though the 2% admixture of wave functions increases the strength by a factor of 15 it is still not a relevant contribution. This leaves the monopole arising from $2\hbar\omega$ excitation (0s to 2s and 1p to 3p) as the remaining possibility of reconciling the three experimental observations.

n. **Sum Rules for M2 and Other Cases** (D. Kurath)

Sum rules were derived for parity-changing operators consisting of an odd-ℓ spherical harmonic coupled to the spin operator sigma. The conditions are that the valence nucleons are in the oscillator shell with Q quanta and the shell with Q-1 quanta is full and the shell with Q+1 quanta is empty. Thus this applies to the 1p,2sd and 3pf as valence shells, where the sum rules would be useful for inelastic electron scattering and other reactions. In particular a complete M2 sum rule was derived including the weak contribution from the orbital operator. The contribution from the spurious center-of-mass motion was also derived. The expression was tested by comparing to summations of transition strengths given by shell-model calculations.

For nuclei with mass greater than ~A = 70 one would need to include the effect of the intruding level with Q+1 quanta and J = Q+3/2. This problem will be considered in the coming year.

D. ATOMIC PHYSICS

a. Reaction (γ,2e) and (e,3e) as Probe of Electron Correlation in Atoms
(M. Ya. Amusia)

Cross sections of the (γ,2e) and (e,3e) reactions contain information about the two vacancy-energy spectrum and electron-pair correlations in initial and final states of the target atom. Physical pictures of these processes are presented for two- and many-electron atoms. The simplest mechanisms are discussed, demonstrating some features which await experimental confirmation. Attention is given to high photon energy and the relativistic energy region of these reactions. The energy distribution of outgoing relativistic electrons is qualitatively different from the nonrelativistic case. The origin and types of corrections to the simplest mechanisms, and possible means of their detection, are discussed. In addition, the role of different resonances: shape, giant, autoionizational, and Feshbach-type are considered. Results of calculations are compared with experimental data, mainly on double photoionization cross sections. Different possible objects as targets for the reactions are considered, including negative ions, excited atoms, molecules, and clusters. The modification of these reactions due to photon emission is discussed. The future of the domain is outlined. A paper on this research was published.

b. On the Continuous Spectrum Electromagnetic Radiation in Electron-Fullerene Collisions (M. Ya. Amusia)

It is demonstrated that the electromagnetic radiation spectrum in electron-fullerene collisions is dominated by a huge maximum of multielectron nature, similar to that already predicted and observed in photoabsorption. Due to coherence, the intensity of this radiation is much stronger than the sum of the intensities of isolated atoms. Experimental detection of such radiation would be of great importance for understanding the mechanism of its formation and for investigating fullerene structures. A paper describing these results was published.

c. Resonant Structure of the 3d Electron's Angular Distribution in a Free Mn^+ Ion (M. Ya. Amusia and V. K. Dolmatov*)

The 3d-electron angular anisotropy parameter of the free Mn^+ ion is calculated using the "spin-polarized" random-phase approximation with exchange. Strong resonance structure is discovered, which is due to interference with the powerful 3p → 3d discrete excitation. The effect of the 3p → 4s transition is also noticeable. The ordering of these respective resonances with phonon energy increase proved to be opposite in angular anisotropy parameter to that in 3d-photoionization cross section. A paper describing these results was published.

*II Institut für Expirementalphysik, Universität Hamburg, Germany.

d. Coherent Correlation Enhancement of Outer Shell Photoionization Cross Sections of Alkali-Like Ions (M. Ya. Amusia, B. Avdonina,* and R. H. Pratt*)

An alkali-like ion interaction with inner electrons of an alkali-like ion leads to a significant increase in the photoionization cross section of the outer s electron. This occurs not only for ground-state ions with one s electron in the outer shell, but also when the outer s electron is in an excited state. The reason for this amplification, in addition to coherent enhancement in summing of the correlation amplitudes, is that the zero in the direct amplitude occurs below threshold. This leads to a constructive interference with the correlation amplitude above the photoionization threshold, in contrast to a destructive interference in the case of a neutral atom with the same electronic configuration, for which the zero occurs above threshold. Results of this research were published.

*University of Pittsburgh.

e. Double Electron Ionization in Compton Scattering of High Energy Photons by Helium Atoms (M. Ya. Amusia and A. I. Mikhailov*)

The cross section for double-electron ionization of two-electron atoms and ions in Compton scattering of high energy photons is calculated. It is demonstrated that its dependence on the incoming photon frequency is the same as that for single-electron ionization. The ratio of "double-to-single" ionization in Compton scattering was found to be energy independent and almost identical with the corresponding value for photoionization. For the He atom it is 1.68%. This surprising result deserves experimental verification.

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*St. Petersburg Nuclear Physics Institute, Gatchina, Russia.

f. On the Difference in Oscillator Strengths of Inner Shell Excitations in Noble Gases and Their Alkali Neighbors (M. Ya. Amusia, A. S. Baltenkov,* and G. I. Zhuravleva*)

It is demonstrated that the oscillator strength of resonant inner-shell excitation in a noble gas atom is considerably smaller than that in its alkali neighbor because in the latter case the effective charge acting upon excited electron is much bigger. With increase of the excitation's principal quantum number the difference between line intensities in noble gases and their alkali neighbors rapidly disappears. The calculations are performed in the Hartree-Fock approximation and with inclusion of rearrangement effects due to inner vacancy creation and its Auger decay. A paper has been submitted for publication.

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*U. Arifov Institute of Electronics, Tashkent, Uzbekistan.

V. ATOMIC AND MOLECULAR PHYSICS RESEARCH

This year, Atomic Physics focused on research programs in the Physics Division in two principal areas: (1) Accelerator-based atomic physics, (2) Synchrotron radiation-based atomic physics.

Within these areas, the scientific interest is in 1) atomic-structure measurements with emphasis on precision measurements useful in testing many-body relativistic atomic calculations, and 2) photon-atom interactions at high photon energies. The experimental research emphasizes the development and use of state-of-the-art experimental techniques to address current problems in atomic physics and simultaneously to utilize the unique facilities available at Argonne, namely, ATLAS, BLASE, and soon, the Advanced Photon Source (APS). In addition, pursuit of interesting scientific questions has led to collaborative experiments at GSI and MSU. The focus of the synchrotron-based program is the development of experiments at the NSLS for future use at the APS as well as the design of the atomic physics endstation. The APS is expected to be available for atomic physics experiments in 1996.

The ATLAS-based program in atomic structure had three thrust areas during the past year: 1) the development of a two-foil technique to measure ultrashort lifetimes in the 100 fs to 10 ps regime for highly-charged ions, 2) the measurement of the spectral distribution of the two-photon decay in helium-like systems, and, 3) the VUV spectroscopy program which shifted emphasis from 2-electron systems to 3-,4- and 5-electron systems. In general, the highly stripped ions available at ATLAS have strong electromagnetic forces acting on sufficiently simple systems to provide a good test of theories. In addition, studies of the dynamics of collisions of fast highly-charged ions with C_{60} continued. These measurements constitute the highest energy collisional system studied for fullerenes and were extended to search for the weak photon emission branch of the collisionaly-excited system. At BLASE, the precision measurement of lifetimes by the fast-beam laser method continued with the aim of understanding systematics thoroughly. In addition, an alternative technique, time-correlated single-photon counting on a thermal atomic beam, was demonstrated to yield comparable accuracy in lifetime measurement (±0.2 - 0.3%). Application of the latter technique to a single trapped Ba^+ ion is anticipated to yield unprecedented accuracy (<0.1%) in lifetime measurements.

The synchrotron-based atomic physics program continues as part of a lab-wide initiative in support of the 7-GeV Advanced Photon Source (APS). In this program, photo-attenuation cross sections of helium in the x-ray region were measured with a precision of 1-2%. The measurements verify the dominance of Compton scattering in this energy range and its importance in recent measurements of the ratio of double-to-single photoionization of helium. Absorption spectroscopy was used to study atomic structure near the K-edge in alkalis and relativistic Hartree-Fock codes were used for interpretation of the spectra. In addition, the development of Raman spectroscopy as a structural tool continued and the advantages of Auger resonant Raman spectroscopy for decomposition of complex features in an absorption spectrum were demonstrated. Initial measurements using photon-electron coincidence techniques were performed and extensions of this technique will enable the detailed understanding of complex vacancy decay mechanisms.

The theoretical program was very active due to the presence of Miron Amusia of the A.V. Joffe Institute in St. Petersburg, Russia from May 1993 through October 1994. He collaborated with all aspects of the experimental program, but was especially influential in the synchrotron-based program. In this area, he provided, for example, 1) a theoretical basis for the observation of enhanced photoabsorption cross sections for resonant inner-shell excitations for the alkalis in comparison with their inert gas neighbors, 2) calculations of double electron ionization in Compton scattering in the prototypical He atom, 3) proposals for probing electron correlation in atoms by the $(\gamma,3e)$ reaction. This is discussed in detail in Section IV-Theoretical Physics. Other ongoing theoretical collaborations included D. R. Beck at Michigan Technological University and L. J. Curtis at the University of Toledo.

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 increases the usefulness of ATLAS for atomic physics studies.

A number of outside groups were attracted to the opportunities offered by ATLAS. Atomic structure studies are being pursued by a group from the University of Notre Dame 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. J. Curtis at the University of Toledo, D. A. Church at Texas A&M University, and M. Hass of the Weizmann Institute are also involved in atomic structure experiments at ATLAS.

Atomic physics experiments at ATLAS 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 Notre Dame program utilizes ultraviolet spectroscopy to study transitions within the n=2 shell of two- and three-electron ions. The NIST group is using X-ray spectroscopy to study transitions in one- and two-electron ions. The Bochum group is studying intercombination transitions in highly-charged Mg-like, Al-like and Si-like ions.

a. Measurement of Short Lifetimes in Highly-Charged Ions using a Two-Foil Target (H. G. Berry,* R. W. Dunford, D. S. Gemmell, E. Kanter, C. Kurtz, B. J. Zabransky, and S. Cheng†)

One of the frontiers in the study of the atomic physics of highly-charged ions is the measurement of lifetimes in the 100 fs to 10 ps regime. The standard technique for measuring lifetimes of states in highly-charged ions is the beam-foil time-of-flight method in which the intensity of an emission line is monitored as a function of the separation between the exciting foil and the portion of the beam being viewed by the detector. This method becomes increasingly difficult as the decay lengths of the states of interest become shorter. At a typical beam velocity of 10% of the speed of light, the beam travels 30 microns in a picosecond. The standard beam-foil time-of-flight method necessitates observation of the decay radiation within one or two decay lengths from the foil while preventing the detectors from observing the beam spot at the foil. For short-lived states this requires tight collimation of the detector with a resulting loss in solid angle. We are developing a method for measuring ultrashort atomic lifetimes utilizing a two-foil target.

As a specific case to demonstrate the feasibility of our method, we are studying the decay of the $2\,^3P_2$ level in helium-like Kr^{34+}. This level has a calculated lifetime of 9.5 ps which corresponds to a decay length of 380 μm. For krypton, theory predicts that 90% of the $2\,^3P_2$ states decay via M2 radiation to the ground state. A measurement of the lifetime of this state would contribute to an important current problem which concerns the understanding of atomic structure when both electron correlations and relativistic effects are simultaneously important.

Our target consists of two foils arranged parallel to each other and perpendicular to the beam velocity. The separation between the foils can be varied accurately from a few microns to several mm. In the experiment 700-MeV Kr ions are stripped to the He-like charge state after ATLAS and

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directed to the spectrograph beam line (Area III) where they enter a target chamber containing the two-foil target. In the first foil, some of the ions are excited to the He-like 2 $^3P_2$ charge state. After drifting in the vacuum between the foils, the ions pass through the second foil where ions which remain in the 2 $^3P_2$ level are preferentially stripped to the H-like charge state because of the enhanced loss cross section for n=2 electrons. Those ions which decay to the helium-like ground state between foils preferentially remain in that state after passage though the second foil. As the distance between the foils is increased, the fraction of ions in the H-like charge state decreases because more of the ions have decayed before reaching the second foil. Thus, by monitoring the fraction of the beam in the H-like charge state as a function of the foil separation, one can determine the decay length. The charge states emerging from the second foil are monitored using the Area III spectrograph.

Our initial runs utilizing the two-foil target provided encouraging results. The expected dependence of the 35^+ charge state on the foil separation was confirmed. We also see significant changes in the intensities of all the other charge states emerging from the second foil. We are now trying to understand our results using a computer model of the two-foil target. Another interesting observation in our experiments is that the X-ray intensity measured a fixed distance downbeam of the second foil also varies as a function of the foil separation. This latter effect was exploited to yield a 10% measurement of the lifetime of the He-Like 2 $^3P_2$ level.

b. Spectral Distribution of the Two-Photon Decay of He-Like Krypton (R. Ali,* I. Ahmad, H. G. Berry,† R. W. Dunford, D. S. Gemmell, E. Kanter, C. Kurtz, B. J. Zabransky, P. H. Mokler,‡ A. E. Livingston,§ S. Cheng,¶ and L. Curtis¶)

The 2 $^1S_0$ state in helium-like ions is forbidden to decay to the ground state by the emission of a single photon so the dominant decay mode is emission of two E1 photons. The energies of the individual photons have a continuous distribution with a broad peak at half the transition energy and the sum of the energies of the two photons is equal to the transition energy. The shape of the continuum single-photon spectrum provides a sensitive probe of the calculation of the transition probability for this decay and we have started a program to make a precision measurement of the spectral shape of the decay of the 2 $^1S_0$ level in He-like krypton in order to test the calculations.

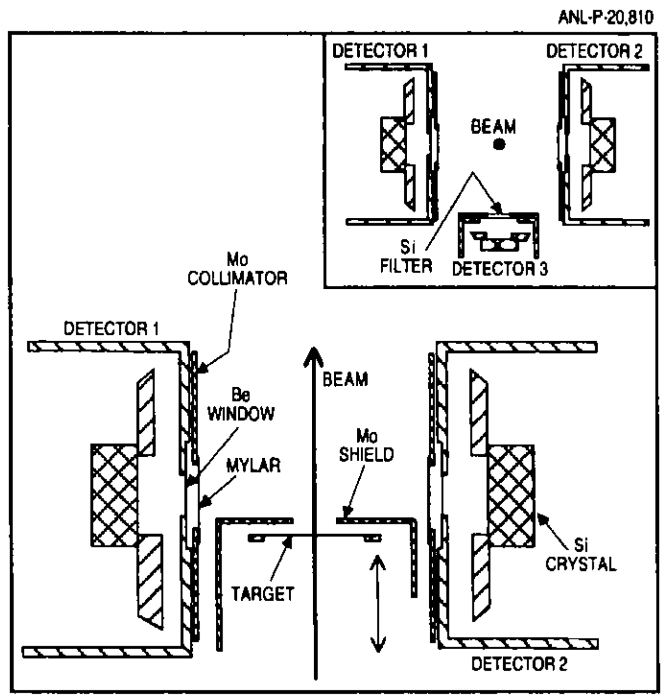

Fig. V-1. Experimental arrangement showing the relationship between the Si(Li) detectors, target, and molybdenum shield.

The first run of the experiment utilized an 805-MeV beam of ^{84}Kr ions provided by ATLAS. The beam was stripped in a 200-μg/cm^2 carbon foil and the 34^+ charge state was magnetically selected and directed to our target chamber. In the chamber, the ions were excited by a 10-μg/cm^2 carbon foil. The region of the beam downstream of the foil was viewed by an array of four X-ray detectors (see Fig. V-1). Two-photon decays were identified as coincidences for which the

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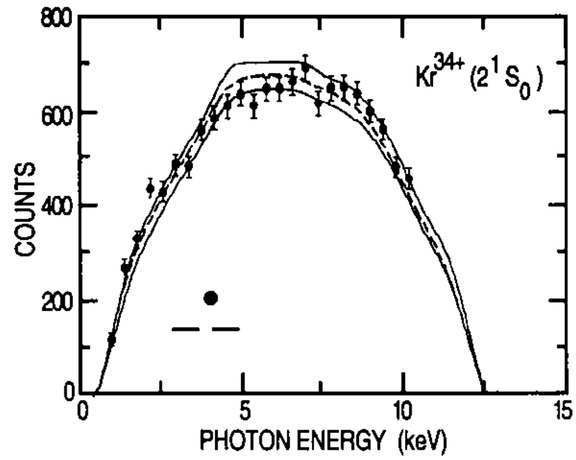

Fig. V-2. Photon energy distributions for the two-photon decays of the $2^1 S_0$ state of Hi-like krypton. The points show the experimental data for one pair of S(Li) detectors. The dashed line is the result of the Monte-Carlo simulation using preliminary efficiency measurements. The errors shown (bars for data, shaded region for simulation) represent statistical uncertainties only.

energies of the two X-rays added up to the transition energy. Analysis of these data is in progress (see Fig. V-2).

The interpretation of our data requires that we determine the coincidence efficiency of our detection system. Several considerations are involved in this. We must characterize both the intrinsic detector efficiency and the efficiency of the acquisition electronics as a function of photon energy. In addition, we must take into account such details as the beam velocity, the decay distribution of beam ions, the angular distribution of decay radiation and the detailed geometry of our detectors. In order to properly account for all of these factors, we developed a Monte-Carlo simulation program to model our experiment. To provide precise information for inclusion in the code, careful measurements were made of the geometry of the foil holders, collimators, and detector crystals. The intrinsic efficiencies of the detectors were determined using a set of radioactive sources whose absolute intensities were measured.

c. Wavelengths and Lifetimes of Transitions in Highly-Ionized Krypton

(H. G. Berry,* R. W. Dunford, D. S. Gemmell, E. P. Kanter, C. Kurtz, B. J. Zabransky, A. E. Livingston,† F. G. Serpa,† and K. Kukla†)

We began a program to test relativistic Hartree-Fock calculations in 3-, 4- and 5- electron systems by making precision wavelength and lifetime measurements. This is an extension of previous work at ATLAS in which we obtained precision lifetime and wavelength measurements in one- and two-electron systems. We are starting by making accurate wavelength and lifetime measurements of the spectra of multielectron krypton in the far ultraviolet region, at wavelengths of 50 to 400 Å. Although there was considerable theoretical progress in this area recently, little accurate data exists for ions above Z=18, except for the wavelengths of the lithium-like transitions.

Our spectra are taken using a beam-foil chamber coupled to a 2.2-m McPherson grazing incidence monochromator. This system was upgraded recently to provide efficient light collection and to take advantage of the time structure of ATLAS. The exit slits of the monochromator were replaced by a position-sensitive channel plate with high spatial and time resolution. The channel plate is mounted on a movable chariot on the Rowland circle of the monochromator. The chariot can be translated along the circle, and it can be rotated about a tangent point of the circle. This latter movement allows us to optimize resolution and efficiency depending on the needs of the experiment. Backgrounds due to electrons, neutrons, gamma rays, and dark count from the detector are greatly reduced using a time window (1-2 ns) triggered from the ATLAS beam pulse structure (82 ns pulse separation).

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d. Positron Production in Heavy-Ion Collisions (R. W. Dunford and the APEX collaboration)

The ATLAS Positron Experiment APEX was built to study positron emission in collisions between very heavy ions. Narrow peaks were observed in such collisions at GSI, Darmstadt in the spectra of positrons and in the sum-energy spectra of electron-positron coincidences. APEX is a second-generation experiment which was specifically designed to look for the coincidence events and measure the opening angle between electrons and positrons. The first beam-induced positrons were detected using APEX in March 1993, and since then three additional runs were carried out. The first results for the collision system $^{238}U + ^{181}Ta$ show no evidence for sharp peaks in the electron-positron sum-energy spectrum.

The current emphasis in this work is to obtain a complete understanding of the APEX apparatus. The atomic group is studying events involving coincidences between heavy ions and electrons. Since APEX measures the laboratory angles and energies of both electrons and heavy ions, it is possible to make an event-by-event Doppler correction of the electron spectra. These Doppler-corrected spectra show a number of lines which are attributed to conversion electrons which are emitted when a nuclear excited state decays by ejecting an inner-shell electron. The study of these spectra provide an important confirmation of the proper functioning of APEX. We are particularly concerned with the atomic physics aspects of this process. In order to understand the electron spectra, it is necessary to account for the change in binding energy of the inner-shell electrons as a function of ionic charge. We are utilizing the GRASP relativistic atomic structure program to calculate the binding energies. This information, together with the measured gamma-ray energies, allows us to calculate the expected energies of the conversion electrons which we can then compare with the observed Doppler-corrected conversion electron energies.

e. RTE and REC in Collisions of U^{90+} Ions on Carbon (R. W. Dunford and the Atomic Physics Group at GSI, Darmstadt)

Data analysis is in progress for atomic-collision experiments done at GSI in Germany. These experiments were designed to study Radiative Electron Capture (REC) and Resonant Transfer and Excitation (RTE) with projectiles of helium-like uranium incident on carbon targets. First results for the photon angular distribution of REC into He-like ions were obtained. This work provides the first study of the photon angular distribution of REC into a projectile p state (j=3/2). This was found to exhibit a slight backward peaking in the laboratory frame. For radiative capture to the j=1/2 states, the angular distribution deviates considerably from symmetry around 90°. The results demonstrate that the usual $\sin^2\theta_{lab}$ distribution is not valid in the high-Z regime.

f. Interactions of High-Energy, Highly-Charged Xe Ions with C_{60} (R. Ali,* H. G. Berry, R. W. Dunford, H. Esbensen, D. S. Gemmell, E. P. Kanter, T. LeBrun, L. Young, W. Bauer,† and S. Cheng‡)

Ionization and fragmentation were measured for C_{60} molecules bombarded in the vapor phase by Xe^{35+} and Xe^{18+} ions with energies in the range 420-625 MeV. The CM energies exceeded those used in previous studies by several orders of magnitude. The mass distribution for the resulting positively charged fragments was determined and we studied the dependence of the fragment yields on the energy and charge of the projectiles. We developed a theoretical model that indicates the total interaction cross section contains roughly equal contributions from a) excitation of the giant plasmon resonance, and b) large-energy-transfer processes leading to multiple fragmentation of the molecule.

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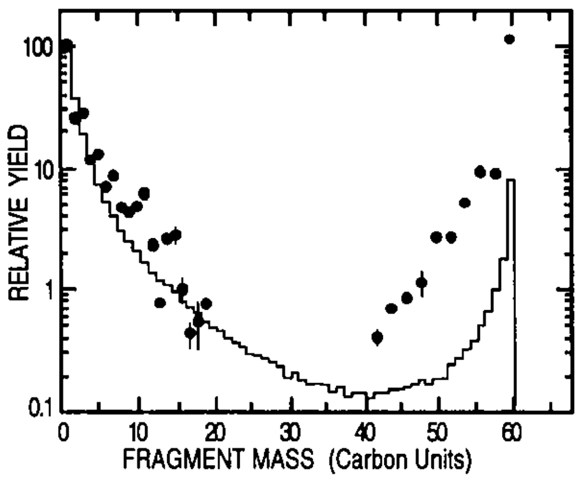

Fig. V-3. Measured mass distribution (solid points) for positive fragments arising from C_{60} *bombarded by 625 MeV* $^{136}Xe^{35+}$ *ions. The histogram is the distribution calculated on the basis of a multifragmentation model analogous to those used to describe nuclear processes.*

There are interesting analogies to giant resonance and multi-fragmentation phenomena observed in nuclear physics and we availed ourselves of some of the theoretical formalisms developed in that field in describing our experimental observations on C_{60} (see Fig. V-3). Additional spectroscopic and lifetime measurements were made on the VUV emissions from the fragments generated in these interactions.

g. Extended Wake Effects in Coulomb Explosions of 35-MeV/amu HeH^+ Ions (M. P. Carpenter, R. W. Dunford, D. S. Gemmell, T. J. Graber,* R. V. F. Janssens, E. P. Kanter, J. A. Nolen, Z. Vager, and B. J. Zabransky)

Our experiments carried out at the Michigan State University National Superconducting Cyclotron Laboratory, aimed at understanding the details of long-range electronic wakes induced in solids by the passage of swift charged particles, proved difficult to analyze because of our lack of knowledge of other ion-solid effects (such as charge changing, multiple scattering, etc.) with such energetic ions. More recently, we carried out additional measurements to study the systematic trends of the Coulomb explosion of 35-MeV/amu HeH^+ ions in a series of different targets (of varying materials and thicknesses). Very recent results reported by a group working at the Indiana University Cyclotron Facility should now help to fix the charge-changing cross sections for such swift He^+ ions. It is hoped that with such data, our Monte-Carlo simulations will now be able to demonstrate the sensitivity of our data to wake effects. This is a crucial step in interpreting the two-foil results recorded in the original experiment.

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*Graduate Student, University of Illinois.

B. FAST-ION-BEAM/LASER STUDIES AT BLASE

The experimental work this year concentrated on the precision lifetime measurement of the first excited p states in neutral lithium by the Notre Dame group of C. E. Tanner and A. E. Livingston in collaboration with H. G. Berry. These measurements are motivated by the theoretical challenges posed by lithium. The three-electron lithium atom is one of the simplest atomic systems with which to test atomic structure calculations. Several recent theoretical calculations of the 2s-2p oscillator strengths agree to 0.15%. However, the precise 1982 fast-beam laser measurement of Gaupp, Kuske, and Andrä (0.15%) differs by 5 sigma from the theory. Hence the need for an independent and precise measurement.

Development of an alternative technique, time-correlated single-photon counting, for precision lifetime measurements continued. Prospects for absolute measurement of lifetimes on a single trapped ion with <0.1% accuracy were evaluated in collaboration with R. G. DeVoe of IBM Almaden Research Center.

a. Precision Lifetime Measurements by Single-Photon Counting (L. Young, W. T. Hill III,* S. R. Leone,† S. Price,‡ S. J. Sibener,§ C. E. Tanner,¶ C. E. Wieman†)

There is renewed interest in the accurate measurement of lifetimes of excited states in alkalis in order to test *ab initio* theories which are needed for the interpretation of atomic parity nonconservation measurements. While it is often assumed that the fast-beam laser method yields the most accurate lifetimes, we demonstrated that an alternative technique, time-correlated single-photon counting, is capable of achieving comparable accuracy. Using this method at JILA, we measured the lifetimes of the 6p $^2P_{1/2}$ and 6p $^2P_{3/2}$ levels in atomic Cs with accuracies ≈0.2-0.3%. A high-repetition rate, femtosecond, self-modelocked Ti:sapphire laser is used to excite Cs produced in a well-collimated atomic beam. The time interval between the excitation pulse and the arrival of a fluorescence photon is measured repetitively until the desired statistics are obtained. The lifetime results are 34.75(7) ns and 30.41(10) ns for the 6p $^2P_{1/2}$ and 6p $^2P_{3/2}$ levels, respectively. These lifetimes are in agreement with those extracted from *ab initio* many-ody perturbation theory calculations at the sub 1% level. The measurement errors are dominated by systematic effects, and methods to alleviate these and approach an accuracy of 0.1% were determined.

Efforts to achieve an unprecedented level of accuracy in lifetime measurements, i.e. <0.1%, using the single-photon counting technique on a single trapped Ba^+ ion are continuing in collaboration with R. G. DeVoe of IBM Almaden Research Center. The Ba^+ ion is isoelectronic to Cs and thus the accurate *ab initio* calculations performed for Cs are directly transportable. The experiment will provide a benchmark value for testing MBPT calculations. The method is directly extendible to lighter alkalis.

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*University of Maryland, †University of Colorado, ‡University College London, §University of Chicago, ¶University of Notre Dame.

b. Hyperfine Structure Studies of Transition Metals (L. Young, C. Kurtz, S. Hasegawa,* D. R. Beck,† and D. Datta†)

This past year our studies of hyperfine structure (hfs) in metastable states of transition metals concentrated on the analysis of hfs in the four-valence electron system, Nb II. Earlier, we measured hfs intervals using the laser-rf double resonance and laser-induced fluorescence methods in a fast-ion beam of Nb^+. The resulting experimental magnetic dipole and electric quadrupole interaction constants are compared to those calculated by a relativistic configuration interaction

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*University of Tokyo, Japan, †Michigan Technological University.

approach. These are the first hfs data on this refractory element. Theoretically, it is found that the most important contributions to the energy are the pair excitations, valence single excitations and core polarization from the shallow core. However, the inner core polarization is found to be crucial for hfs, albeit unimportant for energy. For the J=2 level at 12805 cm^{-1}, $4d^4\ {}^3F$, the theoretical relativistic configuration A-value is in agreement with the experimental result to an accuracy of 4%. Other calculated A-values are expected to be of the same accuracy. A paper describing these results was accepted for publication.

Experimental studies of the four-valence electron system V^+ in the $(4s+3d)^4$ manifold are complete. The theoretical difficulties for the 3d manifold, noted earlier for the three-valence electron Ti^+, as compared to the 4d manifold appear to be repeated in the case of the four-valence electron systems (Nb^+ and V^+). Relativistic configuration interaction calculations are underway, after which a paper will be published.

c. Precision Lifetime Measurements of the 2p Levels in Lithium

(H. G. Berry,* C. Kurtz, C. E. Tanner,† A. E. Livingston,† R. J. Rafac,† and K. W. Kukla†)

These measurements are motivated by the theoretical challenges posed by lithium. The three-electron lithium atom is one of the simplest atomic systems with which to test atomic structure calculations. Recently, there were several *ab initio* calculations of the lithium 2s-2p oscillator strengths, which agree to 0.15%. However, the theoretical results differ by 5 sigma from the precise fast-beam-laser lifetime measurement of Gaupp and Andrä (Berlin). Hence the need for a new independent and precise measurement.

Improvements were added to the fast beam laser techniques developed for cesium in order to measure the lithium 2p state lifetime. Although the technique is similar to that of cesium, the lithium atom presents a few new complications. Since the atom is lighter, it travels more quickly through the interaction and detection regions. Therefore, the 670 nm wavelength requires a dye laser to produce sufficient intensity to populate the excited state. Unfortunately, the intensity of the dye laser is inherently less stable than that of a diode laser. Another complication is that the ion-beam intensity is much more sensitive to fluctuations in the accelerating voltage. Two detectors were added: one to monitor the ion-beam intensity, and the other to monitor the laser power. With the information from the additional detectors, a new data analysis scheme was developed. Sufficient data were taken to evaluate the benefits of the new detectors. No additional work is planned at Argonne for this experiment.

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C. ATOMIC PHYSICS AT SYNCHROTRON LIGHT SOURCES

The research program in atomic, molecular, and optical physics with X-rays complements the program of accelerator-based atomic physics research within the Division. Both programs conduct basic research focused principally on atomic structure. The synchrotron radiation work also enables the study of photon interactions with matter at high energy. The selective nature of the photon excitation provides unique advantages in the detailed study of inner-shell dynamical processes. Much of the current experimental work takes place at the X24A beam line at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. These activities will lay the foundation for the Physics Division's future research in AMO physics at the Advanced Photon Source (APS) at Argonne. We are members of the Basic Energy Sciences Synchrotron Radiation Facility (BESSRC) which will eventually operate two sectors (four beam lines) at the APS. Initially, three beam lines will be instrumented with an undulator, elliptical multipole wiggler and bending magnet. As members we will have access to all three beam lines on a time-share basis with the other members of BESSRC, namely, the ANL programs in materials science, chemistry, and geosciences.

The atomic physics group operates the X24A NSLS beam line jointly with the Quantum Metrology Division of NIST. This agreement provides the group with priority access to this state-of-the-art facility for research in AMO physics with synchrotron radiation. The experiments that we engage in at the NSLS are expected to be transferable to the APS. The experiments utilize diverse techniques, including electron-photon coincidence studies, X-ray resonant Raman spectroscopy, Auger resonant Raman spectroscopy, and X-ray absorption spectroscopy.

a. Attenuation of Photons at 3 to 14 keV Energies in Helium (Y. Azuma,* H. G. Berry,† D. S. Gemmell, J. P. Kirkland,‡ I. Sellin,§ J. Suleiman,¶ M. Westerlind,§ and J. C. Woicik||)

Using X-ray photons at the X24A, X23B and X23A2 beam lines at NSLS, we measured the total photo-attenuation cross section of helium for photons in the energy range of 3 to 14 keV. In this range the photoionization cross section decreases rapidly with energy, so that Compton scattering is significant at 4 keV and dominates at the highest energies. The apparatus consisted of a 1.4-m long helium-absorption tube, 5 cm in diameter, with 75-μ thick, 7-mm diameter, kapton end windows. The tube could be filled with helium up to a pressure of 10^6 Pa. We attained a precision of 1-2% in the attenuation cross section. The measurements verify the dominance of Compton scattering in this energy range and its importance in recent measurements of the ratio of double-to-single photoionization of helium. The measured cross sections are close to the combined calculated cross sections for Compton scattering and photoionization, and we are able to distinguish the contributions of the two effects.

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b. Photoabsorption Spectra of Potassium and Rubidium near the K-Edge (Y. Azuma,* H. G. Berry,† P. L. Cowan,‡ D. S. Gemmell, J. Suleiman,§ and M. Westerlind¶)

We have used a high-temperature circulating heat-pipe absorption cell together with monochromatized X-ray beams at the X24A and X23A2 beam lines at the NSLS to obtain photoabsorption spectra of potassium and rubidium at their K- and KM-edges. The photon-energy

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*Present Address: KEK, Ibaraki-ken, Japan, †Present Address: University of Notre Dame, ‡Deceased, §University of Illinois, Chicago, ¶University of Tennessee.

ranges lay near 3600 eV and 15200 eV, respectively. We have also obtained first measurements of the LII and LIII edges in cesium. Although the K-edge photoabsorptions of the rare gases have been studied, there is little previous work on other atomic vapors. Most of the edges and resonance peaks that we observed have now been identified using Dirac Hartree-Fock calculations. As a check, we have compared these results with those obtained previously in closed-shell rare-gas absorption spectra. The absolute energies were obtained through a calibration of the X24A systems using measurements of several metal L-edges in the 3200-5000 eV energy range. We found that the *4p* resonance in potassium is significantly enhanced compared with the corresponding situation in argon. Likewise, the *5p* resonance in krypton is unresolved from the background ionization cross section, whereas it is well resolved in rubidium. As suggested by Amusia, these enhancements may be due to the enhanced potential seen in the excited state of the alkali systems as a result of the presence of an *s*-electron which reduces the nuclear shielding.

c. X-Ray Resonant Raman Spectroscopy (P. L. Cowan,* T. LeBrun, R. D. Deslattes,† M. MacDonald,† and S. H. Southworth†)

X-ray resonant Raman scattering presents great promise as a high-resolution spectroscopic probe of the electronic structure of matter. Unlike other methods, the technique avoids the loss of energy resolution resulting from the lifetime broadening of short-lived core-excited states. In addition, measurements of polarization and angular anisotropies yield information on the symmetries of electronic states of atoms and molecules.

We studied the L_3 edge of xenon, where the lifetime broadening is a major feature of the spectra recorded previously. X-ray fluorescence spectra were taken of both the $L\alpha_{1,2}$ and $L\beta_{2,15}$ peaks over a range of energies from 10 eV below the edge to 40 eV above. These spectra show the evolution of resonant Raman scattering into characteristic fluorescence as the photon energy is scanned across the edge, and confirm several features of these spectra such as asymmetries in resonant peak shapes due to the onset of the ionization continuum.

These results constitute the most comprehensive study of X-ray resonant Raman scattering to date, and were submitted for publication. Studies of other cases are under way, and new instruments that would match the unique characteristics of the APS — and thus render a new range of experiments possible — are under consideration.

*Deceased, †National Institute of Standards & Technology.

d. Auger Resonant Raman Spectroscopy (Y. Azuma,* T. LeBrun, M. MacDonald,† and S. H. Southworth†)

As noted above, traditional spectroscopy of the electronic structure of the inner shells of atoms, molecules, and solids is limited by the lifetime broadening of the core-excited states. This limitation can also be avoided with the non-radiative analog of X-ray Raman scattering — resonant Auger Raman spectroscopy. We have used this technique to study the K-shell excitation spectrum of argon as the photon energy is continuously scanned across threshold (see Figure V-4).

*Present Address: KEK, Ibaraki-ken, Japan, †National Institute of Standards & Technology.

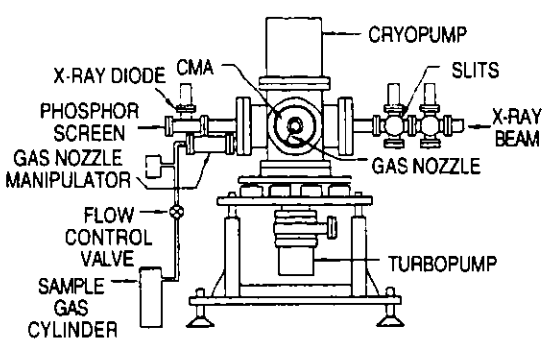

Fig. V-4. Electron spectrometer system used for resonant Raman and coincidence measurements.

The Auger Raman spectrum exhibits the dispersion and line widths characteristic of radiative Raman spectra, but also shows new features such as energy shifts due to charge-state effects that enhance resolution relative to the radiative case. In addition, the measurement of a series of resonant Auger spectra at closely-spaced photon energies permitted the direct observation of features that have previously remained unresolved, such as the onset of the ionization continuum and tails of quasi-discrete states that extend well into the continuum (see Figure V-5). These results were submitted for publication.

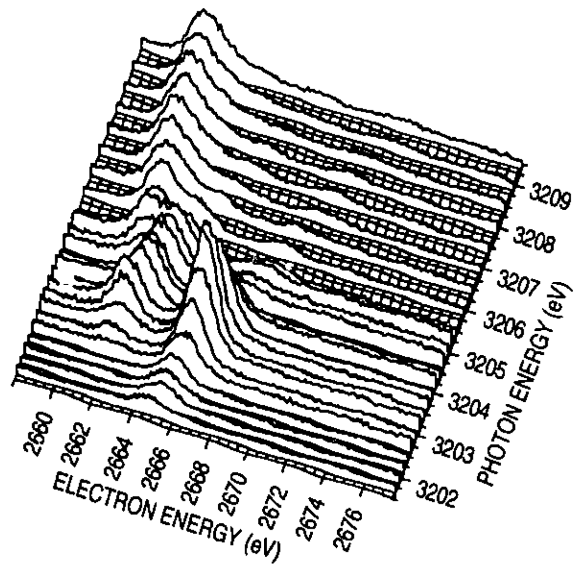

Fig. V-5. Auger resonant Raman spectra near the Ar K edge. The Auger spectra are taken at a series of photon energies closely spaced near the threshold.

As the resolution obtainable with this technique is limited by the bandwidth of the exciting radiation and the lifetime of the final state, we plan to increase our resolution by at least an order of magnitude using the higher flux of the BESSRC undulator at the APS. This should allow us to examine the region near threshold very accurately to enhance our understanding of the physics of this novel process, as well as find evidence for new facets such as continuum resonant Raman scattering for which experimental data is still sketchy.

e. Study of Inner-Shell Vacancy Cascades by Coincidence Techniques
(T. LeBrun, U. Arp,* M. MacDonald,* and S. H. Southworth*)

An inner-shell vacancy in an atom decays by an intricate combination of Auger and fluorescence processes. The interrelation between these processes is not well understood because traditional studies of core-excited atoms focus on only one of the many particles that participate in the relaxation — largely ignoring the other components and the correlations between them.

To understand these correlations we developed a coincidence technique that uses coincident detection of X-rays and electrons to select decay pathways that involve emission of both an X-ray photon and electrons. In the first application of this technique, the Ar 1s photoelectron spectrum was recorded selectively in coincidence with X-ray fluorescence to eliminate the asymmetric broadening and shifting of the energy distribution which results due to post-collision interaction with K-Auger electrons. This allowed the direct observation of the interaction between the photoelectron and the decay of core holes created after the initial photoionization event.

We have also applied this technique to the much more complex problem of understanding Auger-electron spectra produced by vacancy cascades following inner-shell excitation. For example, we previously recorded non-coincident electron spectra of $L_{2,3}MM$ Auger transitions following K-shell excitation of argon. Interpretation of these spectra is difficult because they are complicated and consist of many overlapping or unresolved Auger transitions between different ionic states.

However, these vacancy-cascade electron spectra are much more easily understood when measured in coincidence with X-ray fluorescence. In argon, $K\alpha$ fluorescence accounts for roughly 12% of the total decay of the 1s hole, leading to a state with a single hole in the 2p shell. Recording the $L_{2,3}MM$ Auger spectrum in coincidence with X-ray fluorescence allows the Auger spectrum of the 2p hole produced via initial K-shell excitation to be selectively studied and distinguished from

*National Institute of Standards & Technology.

several other competing processes. The resulting coincidence spectra are relatively simple and straightforward to interpret. This technique is particularly informative for the study of states produced following resonant or near-threshold excitation of the K-shell. These results are currently being prepared for publication. The development of this line of research will be substantially aided by the greater photon intensity from the APS, allowing us to obtain a much more complete understanding of these processes. Additionally, the energy range available from the BESSRC sectors will allow us to study a whole new regime of processes, an area where fluorescence will dominate Auger and the creation of a single core hole can generate a cascade consisting of several tens of decay events.

f. Satellite Structure in the Argon 1s Photoelectron Spectrum (Y. Azuma,* T. LeBrun, M. MacDonald,† and S. H. Southworth†)

Atomic inner-shell photoelectron spectra typically display several relatively weak "satellite peaks" at higher ionization energy than the primary peak. Such satellite peaks are associated with final-state configurations corresponding to ionization of an inner-shell electron and excitation or ionization of one or more valence electrons. The observation of satellite peaks demonstrates that the independent-electron picture is inadequate to describe atomic structure and the photoionization process. The measured energies and intensities of photoelectron satellites provide sensitive tests of many-electron theoretical models.

We recorded the Ar 1s photoelectron spectrum on beam line X-24A at an X-ray energy of 3628 eV. The primary peak at 3206 eV ionization energy was recorded at an observed resolution of 1.8 eV (FWHM). The satellite structure shows remarkable similarity to that recorded in the suprathreshold region of the Ar K photoabsorption cross section, demonstrating the manner in which these techniques complement each other. Surprisingly, while the region just above the K threshold in Ar was the subject of several theoretical studies using multi-configuration calculations, we find good agreement between our results and those of Dyall and collaborators using a shake model.

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*Present Address: KEK, Ibaraki-ken, Japan, †National Institute of Standards & Technology.

g. Atomic Physics at the Advanced Photon Source (H. G. Berry,* P. L. Cowan,† D. S. Gemmell, E. P. Kanter, C. A. Kurtz, T. LeBrun, L. Young, and B. J. Zabransky)

Argonne's 7-GeV synchrotron light source (APS) is expected to commence operations for research early in FY 1996. The Basic Energy Sciences Synchrotron Research Center (BESSRC) is likewise expected to start its research programs at that time. As members of the BESSRC CAT (Collaborative Access Team), we are preparing, together with atomic physicists from the University of Western Michigan, the University of Tennessee, and University of Notre Dame, to initiate a series of atomic physics experiments that exploit the unique capabilities of the APS, especially its high brilliance for photon energies extending from about 3 keV to more than 50 keV. Most of our early work will be conducted on an undulator beam line and we are thus concentrating on various aspects of that beam line and its associated experimental areas. Our group has undertaken responsibilities in such areas as hutch design, evaluation of undulator performance, user policy, interfacing and instrumentation, etc. Initial experiments will probably utilize existing apparatus. We are, however, planning to move rapidly to more sophisticated measurements involving, for example, ion-beam targets, simultaneous laser excitation, and the spectroscopy of emitted photons.

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*Present Address: University of Notre Dame, †Deceased.

OTHER EDUCATIONAL ACTIVITIES IN THE PHYSICS DIVISION

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

As a result of continuing efforts to interact with a large number of minority students, the Minority Program in the ANL Physics Division has succeeded in attracting many highly qualified students to apply for participation in the programs of the Physics Division and other ANL divisions. The program is directed toward the identification of institutions with relatively strong physics programs and with faculty interested in stimulating their students to pursue research activities, particularly 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, 42 applications were received for the summer program in 1994. A total of 24 offers were made for the Summer Research Participation program in conjunction with Argonne's Department of Educational Programs. A number of former participants are currently enrolled in graduate programs in physics; one student is working on his Ph.D. thesis in Nuclear Physics in the Physics Division. Various institutions will be visited during this year and several meetings of minority groups will be attended. These ongoing interactions are 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. Nuclear Physics Award for Faculty in Undergraduate Institutions
(B. Zeidman)

The goal of the "Faculty Program" is to enhance undergraduate science education through faculty awards for minority and historically black colleges and universities (HBCU) faculty that will allow them to participate directly in the ANL Physics Division research program and increase the number of undergraduates involved in research. Although the program was approved late in FY 1994, the Physics Division, with the cooperation of DEP, began the program during the Summer with the appointment of a Hispanic theorist. Undergraduate students are already working with the faculty member who is in the process of preparing an independent funding proposal for continuing research collaboration. It is anticipated that several minority faculty members and their students will be involved in research collaborations in the Physics Division during FY 1995 summer and beyond. In order to extend the limited resources of this program, participants are placed through existing educational programs whenever possible, thereby obtaining supplemental support.

c. Scientific Support of SciTech Museum Exhibits and Outreach Programs
(M. Peshkin)

SciTech (Science and Technology Interactive Center) is a small hands-on science museum located in Aurora, Illinois, not far from Argonne National Laboratory. Its constituency includes prosperous suburbs and economically disadvantaged minority communities in Aurora and Chicago. Its mission is to contribute to the country's scientific literacy initiative by offering hands-on experiences on the museum floor and through outreach programs extended to school children, their teachers, and other groups.

Argonne's participation is focused mainly on the development of exhibits to carry the ideas of modern science and technology to the public. This is an area in which traditional museums are weak, but in which SciTech has become a nationally recognized leader with the assistance of Argonne, Fermilab, nearby technological companies, and many volunteer scientists and engineers. We also participate in development and improvement of the museum's general exhibits and outreach programs. Argonne's Director, Alan Schriesheim, serves as a member of the museum's Board of Directors. Murray Peshkin serves part-time as the museum's Senior Scientist. Dale Henderson serves part-time as an exhibit developer. That work is supported by the Laboratory Director's discretionary funds. In addition, several members of the Physics Division voluntarily assist with exhibit development and the Division makes facilities available for that effort.

d. The $E = mc^2$ Exhibition (D. Henderson and M. Peshkin)

The goal of this DOE-supported exhibition is to demystify Einstein's formula $E = mc^2$ by illustrating the interchangeability of matter (m) and energy (E), c^2 being the exchange rate. The exhibition has two major parts, "matter into energy" and "energy into matter", plus a video to connect them. "Matter into energy" has now been completed and has been placed on the museum floor. Positrons from a ^{22}Na source are annihilated to produce gamma rays that are caught in NaI detectors. The viewer can alter the alignment of the detectors and observe the consequences for the rates of single and coincident counts. The viewer can also observe the effects of placing absorbers in front of the counters. Prototype explanatory graphics were placed around the exhibit and those will probably be changed after we have some experience with their effectiveness. The connecting video is in the process of being produced in collaboration with Fermilab. A cloud chamber for "energy into matter", where gamma rays from a small Th source will produce observable pairs, was purchased and work to make the pairs visible has commenced.

STAFF MEMBERS OF THE PHYSICS DIVISION

Listed below are the staff of the Physics Division for the year ending March 31, 1995.
The program headings indicate only the individual's current primary activity.

EXPERIMENTAL NUCLEAR PHYSICS STAFF

Experimental Staff

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
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
Cheng-lie Jiang, Ph.D. China Institute of Atomic Energy, 1960
Cathleen Jones, Ph.D., California Institute of Technology, 1991
Teng Lek Khoo, Ph.D., McMaster University, 1972
** Walter Kutschera, Ph.D., University of Graz, Austria, 1965
Torben Lauritsen, Ph.D., State University of New York, 1990
Christopher J. Lister, Ph.D., University of Liverpool, 1977
†† Jerry A. Nolen, Jr., Ph.D., Princeton University, 1965
‡‡ Richard C. Pardo, Ph.D., University of Texas, 1976
David H. Potterveld, Ph.D., Caltech, 1988
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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* Joint appointment with the University of Illinois-Chicago as of January 1995.
† Joint appointment with the University of California, Berkeley.
‡ ATLAS User Program Administrator.
§ Director of the Physics Division.
¶ On leave of absence at University of Ilinois-Urbana until June 1995.
‖ Associate Director of the Physics Division.
**On leave of absence at the University of Vienna until August 1995.
†† Director of the ATLAS Facility.
‡‡ ATLAS Operations Manager.
§§ Associate Director of the Physics Division. Joint appointment with the University of Chicago.

Experimental Staff/Special Appointments

- * Lowell M. Bollinger, Ph.D., Cornell University, 1951
- † Melvin S. Freedman, Ph.D., University of Chicago, 1942
- * Sheldon B. Kaufman, Ph.D., University of Chicago, 1953
- * Alexander Langsdorf, Jr., Ph.D., Massachusetts Inst. of Technology, 1937
- * Michael Paul, Ph.D., Hebrew University of Jerusalem, 1973
- * 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 STAFF

Theoretical Physics Staff

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., Flinders University of South Australia, 1989
Robert B. Wiringa, Ph.D., University of Illinois, 1978

Theoretical Staff/Special Appointments

- * Paul Benioff, Ph.D., University of California, 1959
- † Arnold R. Bodmer, Ph.D., Manchester University, 1953
- † Lloyd Hyman, Ph.D., Massachusetts Institute of Technology, 1959
- † Dieter Kurath, Ph.D., University of Chicago, 1951
- † Harry J. Lipkin, Ph.D., Princeton University, 1950
- ‡ Vijay Pandharipande, Ph.D., University of Bombay, 1969
- * Murray Peshkin, Ph.D., Cornell University, 1951

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* Special Term Appointee.
† Resident Associate Guest Appointee.
‡ Special Term Appointee from the University of Illinois, Urbana.

Atomic and Molecular Physics Staff

* 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

Atomic and Molecular Physics Staff/Special Appointments

§ 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

** Richard Harkewicz, Ph.D. Michigan State University, 1992
†† Thomas LeBrun, Ph.D. University of Paris, 1991

POSTDOCTORAL APPOINTEES

Rami Ali (from Kansas State University, Manhattan, Kansas):
Atomic physics at ATLAS.
(August 1993--January 1995)

Axel Bender (University of Tubingen, Germany):
Nuclear theory studies.
(January 1995--)

Daniel Blumenthal (University of Pennsylvania, Philadelphia, Pennsylvania):
Heavy-ion research at ATLAS.
(January 1994--)

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* Left the Physics Division in December 1994 to join the University of Notre Dame.
† Deceased August 1994.
‡ Joint Appointment with Weizmann Institute of Science, Rehovot, Israel.
§ Special Term Appointee.
¶ Resident Associate Guest.
** Postdoctoral Appointee until March 1994. Term appointment to March 1995.
†† Postdoctoral Appointee until July 1994. Term appointment to June 1995.

Benjamin F. Crowell (from Yale University, New Haven, Connecticut):
Heavy-ion research at ATLAS.
(June 1993--)

James Fedchak (from College of William and Mary, Williamsburg, Virginia):
Medium-energy physics.
(October 1994--)

Susan Fischer (from University of Notre Dame, Notre Dame, Indiana):
Heavy-ion research at ATLAS.
(January 1995--)

Jens-Ole Hansen (from Massachusetts Inst. of Technology, Cambridge, Massachusetts):
(Medium-energy studies.
(October 1994--)

*Richard Harkewicz (from Michigan State University, E. Lansing, Michigan):
Accelerator development and research at ATLAS.
(March 1992--March 1994)

Roland Henry (from Rutgers University, New Brunswick, New Jersey):
Heavy-ion physics at ATLAS.
(January 1992--April 1994)

David J. Hofman (from SUNY, Stony Brook, New York):
Heavy-ion research at ATLAS.
(August 1994--)

Martin Jung (from GSI, Darmstadt, Germany):
Atomic physics research.
(December 1994--)

Jong-won Kim (from Michigan State University, E. Lansing, Michigan):
ATLAS development.
(June 1994--)

Bertold Kraessig (from University of Freiburg, Germany):
Atomic physics with synchrotron light sources.
(March 1995--)

†Thomas LeBrun (from University of Paris, France):
Atomic physics using synchrotron light sources.
(November 1991--July 1994)

Naomi Makins (from Massachusetts Inst. of Technology, Cambridge, Massachusetts):
Medium energy physics.
(July 1994--)

Thomas P. O'Neill (from California Inst. of Technology, Pasadena, California):
Medium-energy physics.
(March 1994--)

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* Term appointment as of March 1994.
† Term appointment as of July 1994.

Vassilious Pavassiliou (from Yale University, New Haven, Connecticut):
Medium-energy physics research.
(May 1991--July 1994)

Heikki Penttila (from University of Jyväskylä, Finland):
Research with the FMA at ATLAS
(October 1992--September 1994)

Martin Rhein (from Institut fur Kernphysik, Darmstadt, Germany):
Heavy-ion physics at ATLAS.
(January 1993--January 1995)

Dariusz Seweryniak (from University of Uppsala, Sweden):
Heavy-ion research at ATLAS.
(January 1995--)

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.

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.

*Post-retirement appointee.

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.

Thomas P. Mullen (B.S. Marquette University, 1966).
Division ESH/QA engineer.

Floyd Munson, Jr. (A.A.S. DeVry, 1966, B.S. Lewis University, 1993).
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.

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.

Anne Sutherland (B.S. University of Rochester, 1993).
Operate, upgrade and maintain ATLAS cryogenic system.

Brian J. Tieman (B. A. North Central College, 1992).
ATLAS operator.

Ian R. Tilbrook (B.S. Pennsylvania State University, 1987; MBA, Keller Graduate School of Management, 1994).
ATLAS operator.

Richard Vondrasek (B.S. University of Illinois, 1990).
ATLAS operator.

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. Medium-energy physics.

Gary P. Zinkann (B.S. DeVry, 1975).
ATLAS operations supervisor.

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*In charge of Dynamitron operations.

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)

§Miron Amusia (Ioffe Institute, St. Petersburg, Russia):
Atomic physics research.
(May 1993--October 1994)

Michael Bruns (University of Lübeck):
ATLAS Development.
(September 1994--)

Tarun Changrani (Nuclear Science Centre, New Delhi, India):
ATLAS Development.
(July 1994--January 1995)

Thomas Dossing (University of Copenhagen):
Heavy-ion research.
(September 1993--August 1994)

David Gassmann (Technical University of Munich, Germany):
Heavy-ion research at ATLAS.
(January-December 1994)

Robert Hermann (Technical University of Munich, Germany):
Heavy-ion research at ATLAS.
(June 1993--June 1994)

¶ Cheng-Lie Jiang (China Institute of Atomic Energy, Beijing, China):
Heavy-ion research at ATLAS.
(October 1992--November 1994)

Debdulal Kabiraj (Nuclear Science Centre, New Delhi, India):
Target-making techniques.
(October 1994--)

Ajith Kumar (Nuclear Science Centre, New Delhi, India):
ATLAS development.
(January 1994--November 1994)

‖ Donald McLeod (University of Illinois, Chicago, Illinois):
Heavy-ion research at ATLAS.
(June 1994--)

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* Assistant Director of the Physics Division.
† Manager, Division Operations.
§ 1993-94 Argonne Fellow.
¶ Joined regular staff in November 1994.
‖ Faculty Research Participant.

* Nora Mansour (Western Michigan University, Kalamazoo, Michigan):
Atomic physics research.
(October 1991--   )

Rajeev Mehta (Nuclear Science Centre, New Delhi, India):
ATLAS development.
(February 1995--   )

Suryanarayana Muralidhar (Nuclear Science Center, New Delhi, India):
ATLAS development.
(July 1994--January 1995)

Amit Roy (Nuclear Science Center, New Delhi, India):
ATLAS development.
(January --June 1994; January 1995--   )

Norbert Schmidt (Fachhochschule, Munich, Germany):
Heavy-ion research at ATLAS.
(March 1994--August 1994)

* Carol Tanner (University of Notre Dame, Indiana):
Atomic physics at BLASE.
(March 1992--   )

† Guangsheng Xu (Yale University, New Haven, Connecticut):
Heavy-ion research at ATLAS.
(January 1994--   )

<u>SHORT-TERM VISITORS</u> (at ANL less than 4 months)

Reinhard Alkofer (Tubingen University, Germany):
Nuclear theory studies.
(August-September 1994)

Isaac Chappell (Massachusetts Institute of Technology, Cambridge, Massachusetts):
Nuclear theory studies.
(May-August 1994)

‡ Richardo Cossyleon (Benito Juarez High School, Cicero, Illinois):
Medium-energy physics.
(July-August 1994)

Fred de Jong (University of Georgia, Athens, Georgia):
Nuclear theory studies.
(June-July 1994)

Ameenah Farhan (University of Kuait):
Nuclear theory studies.
(October-November 1994)

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* Guest Faculty Research Participant.
† Faculty Research Participant.
‡ DOE Trac Teacher 1994.

David Gassman (Technical University of Munich, Germany):
Heavy-ion Research at ATLAS.
(January-February 1995)

* Edward Hohman (York Township High School, Lyons, Illinois):
Summer student coordinator.
(June--August 1993)

Yasha Levin (Weizmann Institute of Science, Rehovoth, Israel):
Atomic physics studies.
(July-August 1994)

† Jorge A. Lopez (University of Texas, El Paso, Texas):
Nuclear theory.
(May-June 1994)

Stanislav Popov (Institute for Nuclear Physics, Novosibirsk, Russia):
Medium-energy physics studies.
(August-September 1994)

† Akunuri Ramayya (Vanderbilt University, Nashville, Tennessee):
Heavy-ion research at ATLAS.
(June--July 1994)

‡ Thomas J. Regan III (Los Altos High School, Los Altos, California):
Medium-energy physics.
(June-August 1994)

Dmitri Toporkov (Institute for Nuclear Physics, Novosibirsk, Russia):
Medium-energy physics.
(August-September 1994)

Daniel Zajfman (Weizmann Institute of Science, Rehovoth, Israel):
Accelerator-based atomic physics.
(August 1994)

RESIDENT GRADUATE STUDENTS

Hanan Amro (North Carolina State University, Raleigh, North Carolina):
Heavy-ion Research at ATLAS.
(January 1995--)

Kevin Beyer (Michigan State University, E. Lansing, Michigan):
Heavy-ion research at ATLAS.
(August 1992--)

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* Guest Faculty Research Participant. Summer student coordinator.
† Faculty Research Participant.
‡ 1993 DOE Trac Teacher.

Kanwarjit S. Bindra (Vanderbilt University, Nashville, Tennessee):
FMA development at ATLAS.
(May 1990--July 1994)

Larry Brown (Vanderbilt University, Nashville, Tennessee):
FMA development at ATLAS
(January 1994--)

Brian Busse (Oregon State University, Corvallis, Oregon):
FMA development at ATLAS.
(June 1994--)

Kin Chi Chan (Yale University, New Haven, Connecticut):
APEX experiment at ATLAS.
(June 1992--July 1994)

Christopher Conner (University of Illinois-Chicago):
Heavy-ion research at ATLAS.
(June 1994--)

Louis Conticchio (University of Maryland, College Park, Maryland):
Heavy-ion research at ATLAS.
(October 1994--)

John C. Gehring (University of Chicago, Chicago, Illiniois):
Heavy-ion research at ATLAS.
(June 1990--)

Nicholas Kaloskamis (Yale University, New Haven, Connecticut):
APEX experiment at ATLAS.
(November 1991--May 1994)

Manquing Liu (Queen's University, Kingston, Ontario, Canada):
APEX experiment at ATLAS.
(September 1992--March 1994)

David Nisius (Purdue Univ ersity, W. Lafayette, Indiana):
Heavy-ion research at ATLAS.
(June 1993 --)

Aloy Perera (University of Rochester, Rochester, New York):
APEX experiment at ATLAS.
(August 1993 --)

Michael Pichowsky (University of Pittsburgh, Pennsylvania):
Theoretical physics studies.
(September 1993--)

Dante Roa (Florida State University):
Research with APEX at ATLAS.
(May 1992--)

Michael Rogers (University of Iowa, Ames, Iowa):
Nuclear theory studies.
(March 1994--)

Jamal Suleiman (University of Illinois, Chicago, Illinois):
Atomic physics research.
(October 1991--October 1994)

Mark Wolanski (University of Chicago, Chicago, Illinois):
Weak interaction studies.
(July 1991--)

Guest Graduate Students

Konstantin Akimov (University of Illinois, Chicago, Illinois):
Heavy-ion research at ATLAS.
(May 1994--)

Dipangkar Dutta (Northwestern University, Evanston, Illinois):
Medium-energy studies.
(June 1994--)

Robert Rafac (University of Notre Dame, Notre Dame, Indiana):
Atomic physics research.
(March 1992--)

UNDERGRADUATE STUDENTS

Erik Alldredge (Worcester Polytechnic Institute)
Gordon Annan (Dillard University)
Teresa Barlow (Illinois Benedictine College)
Jonathan Brumley (Rice University)
Isaac Chappell (Massachusetts Institute of Technology)
Diane Eschliman Nebraska Wesleyan University)
William Huttner (Florida State University)
Walter Jackson (Tougaloo College)
Morgan Johnson (Lincoln University)
Steven Kramer (Lewis University)
Jay Kreibich (University of Illiinois-Urbana)
Evelyn Livoti (State University of New York College)
Richard Pelaia (Florida Institute of Technology)
Mauricio Portillo (University of Texas, El Paso)
Heidi Reichenbach (University of Notre Dame)
Christian Roehrig (North Central College)
Stacey Schiel (North Central College)
Wilson Sheppard (Southern University and A&M College)
Teresa Soledad (University of Illinois - Urbana)
Rachel Smith (Kalamazoo College)
David Sowinski (Lewis University)
Christopher Stepanek (College of St. Francis)
Jared Torres (Loyola University)
Dale Visser (Western Michigan University)
Kimberly Woody (Kalamazoo College)
Sean Wooten (Xavier University)

PRE-COLLEGE PROGRAM (Just Graduated from High School)
(June--August 1994)

Teresa Barlow (Naperville Central High School)
Daniel Braithwaite (Oak Park/River Forest High School)
John Frederiksen (Maine Township High School)
Erika Hill (Whitney-Young Magnet High School)
Max Schoenberg (Hinsdale Central High School)

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John P. Schiffer
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G. J. Lane, G. D. Dracoulis, A. P. Byrne, P. M. Walker, A. M. Baxter, R. G. Henry, D. Nisius, C. N. Davids, T. Lauritsen, H. Penttilä, D. J. Henderson, J. A. Sheikh, and W. Nazarewicz
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Superdeformed Bands with a Unique Decay Pattern: Possible Evidence for Octupole Vibration in ^{190}Hg
B. Crowell, R. V. F. Janssens, M. P. Carpenter, I. Ahmad, S. Harfenist, R. G. Henry, T. L. Khoo, T. Lauritsen, D. Nisius, A. N. Wilson, J. F. Sharpey-Schafer, and J. Skalski
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J. A. Shannon, W. R. Phillips, J. L. Durell, B. J. Varley, W. Urban, C. J. Pearson, I. Ahmad, C. J. Lister, L. R. Morss, K. L. Nash, C. W. Williams, N. Schulz, E. Lubkiewicz, and M. Bentlab
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Gamma-Ray Studies of ^{119,121,123}Sn Isomers Formed in Deep Inelastic Heavy Ion Collisions
R. H. Mayer, D. Nisius, I. G. Bearden, P. Bhattacharyya, L. Richter, M. Sferrazza, Z. W. Grabowski, P. J. Daly, R. Broda, B. Fornal, I. Ahmad, M. P. Carpenter, R. G. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, and J. Blomqvist
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Observation of the One- to Six-Neutron Transfer Reactions at Sub-Barrier Energies
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"Identical" Superdeformed Band in ^{151}Dy: Further Evidence for the Pseudospin Coupling Scheme
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Phys. Lett. B346, 15-20 (1995)

Viscosity of Saddle-to-Scission Motion in Hot ^{240}Cf from GDR γ Yield
D. J. Hofman, B. B. Back, I. Dioszegi, C. P. Montoya, S. Schadmand, R. Varma, and P. Paul
Phys. Rev. Lett. 72, 470 (1994)

Lifetime Measurement in Excited and Yrast Superdeformed Bands in ^{194}Hg
J. R. Hughes, I. Ahmad, J. A. Becker, M. J. Brinkman, M. P. Carpenter, B. Cederwall, M. A. Deleplanque, R. M. Diamond, J. E. Draper, C. Duyar, P. Fallon, S. Harfenist, E. A. Henry, R. G. Henry, R. W. Hoff, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, I. Y. Lee, E. Rubel, F. S. Stephens, and M. A. Stoyer
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New Features of Superdeformed Bands in ^{194}Hg

B. Cederwall, R. V. F. Janssens, M. J. Brinkman, I. Y. Lee, I. Ahmad, J. A. Becker, M. P. Carpenter, B. Crowell, M. A. Deleplanque, R. M. Diamond, J. E. Draper, C. Duyar, L. P. Farris, P. Fallon, E. A. Henry, R. G. Henry, J. R. Hughes, T. L. Khoo, T. Lauritsen, A. O. Macchiavelli, E. Rubel, F. S. Stephens, M. A. Stoyer, W. Satula, I. Wiedenhoever, and R. Wyss

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B. Crowell, P. Chowdhury, S. J. Freeman, C. J. Lister, M. P. Carpenter, R. G. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, F. Soramel, and I. G. Bearden

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D. Miskowiec, W. Ahner, R. Barth, M. Cieslak, M. Debowski, E. Grosse, W. Henning, P. Koczon, R. Schicker, E. Schwab, P. Senger, P. Baltes, Ch. Muntz, H. Oeschler, S. Sartorius, Ch. Sturn, A. Wagner, P. Beckerle, Ch. Bormann, D. Brill, Y. Shinn, J. Stein, R. Stock, H. Strobele, B. Kohlmeyer, H. Poppl, F. Puhlhofer, J. Speer, K. Volkel, and W. Walus

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B. Crowell, P. Chowdhury, S. J. Freeman, C. J. Lister, M. P. Carpenter, R. G. Henry, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, Y. Liang, F. Soramel, And I. G. Bearden

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Proton Inelastic Scattering on ^{56}Ni in Inverse Kinematics

G. Kraus, P. Egelhof, C. Fischer, H. Geissel, A. Himmler, F. Nickel, G. Munzenberg, W. Schwab, A. Weiss, J. Friese, A. Gillitzer, H. J. Korner, M. Peter, W. F. Henning, J. P. Schiffer, J. V. Kratz, L. Chulkov, M. Golovkov, A. Ogloblin, and B. A. Brown

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Lifetimes in Neutron-Rich Nd Isotopes Measured by a Doppler Profile Method

A. G. Smith, W. R. Phillips, J. L. Durell, W. Urban, B. J. Varley, C. J. Pearson, J. A. Shannon, I. Ahmad, C. J. Lister, L. R. Morss, K. L. Nash, C. W. Williams, M. Bentaleb, E. Lubkiewicz, and N. Schulz

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Anomalous Schottky Signals from a Laser-Cooled Ion Beam

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Measurement of the Lifetime of the 2 $^3P_2$ State in Heliumlike Krypton using a Two-Foil Target
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Mass Asymmetry Dependence of Scission Times in the Reactions of 18.5 A MeV ^{136}Xe + ^{48}Ti
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Study of the β-Delayed Neutron Decay of ^{18}N
K. W. Scheller, J. Gorres, J. G. Ross, M. Wiescher, R. Harkewicz, D. J. Morrissey, B. N. Sherrill, M. Steiner, N. A. Orr, and J. A. Winger
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Superdeformed Bands in ^{191}Tl
S. Pilotte, C. H. Yu, H. Q. Jin, J. M. Lewis, L. L. Riedinger, Y. Liang, R. V. F. Janssens, M. P. Carpenter, T. L. Khoo, T. Lauritsen, F. Soramel, I. G. Bearden, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, and F. K. McGowan
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Phy. Rev. C 49, 948-954 (1994)

Selective Population of States in Fission Fragments from the ^{32}S + ^{24}Mg Reaction
S. J. Sanders, A. T. Hasan, F. W. Prosser, B. B. Back, R. R. Betts, M. P. Carpenter, D. J. Henderson, R. V. F. Janssens, T. L. Khoo, E. F. Moore, P. Wilt, F. L. H. Wolfs, A. H. Wuosmaa, K. B. Beard, and P. Benet
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Heavy-Ion Resonance and Statistical Fission Competition in the ^{24}Mg + ^{24}Mg System at $E_{c.m.}$ = 44.4 MeV
A. T. Hasan, S. J. Sanders, K. A. Farrar, F. W. Prosser, B. B. Back, R. R. Betts, M. Freer, D. J. Henderson, R. V. F. Janssens, A. H. Wuosmaa, and A. Szanto de Toledo
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Gamma Ray Studies of Neutron-Rich sdf Shell Nuclei Produced in Heavy Ion Collisions
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Phys. Rev. C 49, 2413 (1994)

Reply to "Comment on 'Lack of Evidence for a Superdeformed Band in ^{192}Pb'"
A. J. M. Plompen, M. N. Harakeh, W. H. A. Hesselink, G. van't Hof, N. Kalantar-Nayestanaki, J. P. S. van Schagen, R. V. F. Janssens, I. Ahmad, I. G. Bearden, M. P. Carpenter, T. L. Khoo, T. Lauritsen, Y. Liang, U. Garg, W. Reviol, and D. Ye
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W. Reviol, L. L. Riedinger, J. Y. Zhang, C. R. Bingham, W. F. Mueller, B. E. Zimmerman, R. V. F. Janssens, M. P. Carpenter, I. Ahmad, I. G. Bearden, R. G. Henry, T. L. Khoo, T. Lauritsen, and Y. Liang
Phys. Rev. C <u>49</u>, R587-591 (1994)

Limits for the 3α Branching Ratio of the Decay of the 7.65 MeV, 0^+ State in ^{12}C
M. Freer, A. H. Wuosmaa, R. R. Betts, D. J. Henderson, P. Wilt, R. W. Zurmuhle, D. P. Balamuth, S. Barrow, D. Benton, Q. Li, Z. Liu, and Y. Miao
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B. Crowell, P. J. Ennis, C. J. Lister, and W. R. Schief
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Angular Distribution Measurements for $^{12}C(^{12}C,^{12}C(0_2^+))^{12}C(0_2^+)$ Inelastic Scattering
A. H. Wuosmaa, M. Freer, B. B. Back, R. R. Betts, J. C. Gehring, B. G. Glagola, Th. Happ, D. J. Henderson, P. Wilt, and I. G. Bearden
Phys. Rev. C <u>50</u>, 2909-2916 (1994)

Low-Lying Structure of the Neutron Deficient Isotope ^{202}Rn
S. J. Freeman, B. B. Back, J. Becker, I. G. Bearden, D. J. Blumenthal, M. P. Carpenter, P. Chowdhury, B. Crowell, C. N. Davids, D. Henderson, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, C. J. Lister, E. F. Moore, D. Nisius, H. T. Penttilä, A. G. Smith, and S. J. Warburton
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E. F. Moore, M. P. Carpenter, Y. Liang, R. V. F. Janssens, I. Ahmad, I. G. Bearden, P. J. Daly, M. W. Drigert, B. Fornal, U. Garg, Z. W. Grabowski, H. L. Harrington, R. G. Henry, T. L. Khoo, T. Lauritsen, R. H. Mayer, D. Nisius, W. Reviol, and M. Sferrazza
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C. N. Davids
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D. J. Mercer, D. Mikolas, J. Yurkon, S. M. Austin, D. Bazin, S. Gaff, E. Kashy, D. Kataria, J. S. Winfield, R. R. Betts, D. Henderson, A. Hallin, and M. Liu
Nucl. Instrum. Methods A348, 252-255 (1994)

A Large Solid-Angle Array for Heavy Ions from APEX
D. J. Mercer, D. Mikolas, J. Yurkon, S. M. Austin, D. Bazin, S. Gaff, E. Kashy, D. Kataria, J. S. Winfield, R. R. Betts, D. J. Henderson, A. L. Hallin, M. Liu, and F. L. H. Wolfs
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W. Kutschera, M. Paul, I. Ahmad, T. A. Antaya, P. J. Billquist, B. G. Glagola, R. Harkewicz, M. Hellstrom, D. J. Morrissey, R. C. Pardo, K. E. Rehm, B. M. Sherrill, and M. Steiner
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Level Structure of the Odd-Odd Nucleus $^{224}_{89}$Ac
I. Ahmad, J. E. Gindler, M. P. Carpenter, D. J. Henderson, E. F. Moore, R. V. F. Janssens, I. G. Bearden, and C. C. Foster
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New Results on the Superdeformed Band in ^{192}Hg
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