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Introduction

This report summarizes the activities of the Nuclear Science Division during the period October 1, 1984 to September 30, 1985. As in previous years, experimental research has for the most part been carried out using our three local accelerators, the Bevalac, the SuperHILAC and the 88-Inch Cyclotron. However, during this time, preparations began for a new generation of relativistic heavy-ion experiments at CERN. The Nuclear Science Division is involved in three major experiments at CERN and several smaller ones. It is clear that with these experiments and the new heavy-ion program starting up at the Brookhaven AGS, work away from our home institution will be a new and challenging fact of life of many members of the Nuclear Science Division.

The year was a very productive one at the Bevalac. Beautiful results continued to be obtained by the Plastic Ball collaboration. The most important was the extraction of information on the nuclear equation of state that confirms the earlier results from the Streamer Chamber obtained using a very different technique. Other highlights of Bevalac research included systematic measurements of the interaction cross sections of secondary radioactive beams, new insights into the reaction mechanism of medium energy collisions and a new measurement of the Lamb shift in Helium-like Uranium.

At the 88-Inch Cyclotron, the program has gained in strength and popularity, witnessed by the increased demand for beam time. The principal reason for this has been the outstanding performance of the new ECR (Electron Cyclotron Resonance) ion source. The cyclotron now produces beams of unprecedented energy and reliability that are being used for studies of nuclear structure and reaction mechanisms.

The report is divided into 5 sections. Part I describes the research programs and operations, and Part II contains condensations of experimental papers arranged roughly according to program and in order of increasing energy, without any further subdivisions. Part III contains condensations of theoretical papers, again ordered according to program but in order of decreasing energy. Improvements and innovations in instrumentation and in experimental or analytical techniques are presented in Part IV. Part V consists of appendices, the first listing publications by author for this period, in which the LBL report number only is given for papers that have not yet appeared in journals; the second contains abstracts of PhD theses awarded during this period; and the third gives the titles and speakers of the NSD Monday seminars, the Bevatron Research Meetings and the theory seminars that were given during the report period. The last appendix is an author index for this report.

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PART I: PROGRAMS

Exotic Nuclei and Decay Modes

Studies of nuclei far from the valley of stability can provide tests of theoretical models which predict the existence, masses, and shapes of exotic nuclei. These studies have revealed new modes of radioactive decay while providing spectroscopic data on nuclides with unusually high proton to neutron ratios. Exotic nuclei, which are expected to define the proton drip line in the light mass region, have been produced in low yield reactions at the 88-Inch Cyclotron.

In the past, the $T_z = -2$ nuclei ^{22}Al and ^{26}P were discovered via their beta-delayed proton decay and were later shown to produce beta-delayed two-proton radioactivity. This year the first $T_z = -5/2$ nucleus, ^{35}Ca , was discovered via its beta-delayed two-proton decay. Thus, for the first time this relatively new mode of decay was used as an effective tool in the search for exotic nuclei near the proton drip line. In addition to the light mass beta-delayed two-proton emitters already observed, heavier nuclei are also expected to exhibit this decay mode. Preliminary searches for ^{46}Mn and ^{50}Co have been conducted but, as yet, the results are inconclusive.

The beta-delayed single proton emissions from the $T_z = -3/2$ nuclei ^{27}P and ^{31}Cl have been studied. Although ^{26}P had been previously observed, ^{27}P was still uncharacterized. This observation of ^{27}P completes the series of beta-delayed proton emitters with $T_z = -3/2$ in the sd-shell. Several new proton groups were attributed to the decay of ^{31}Cl . The decays of these two nuclei were compared to a complete (sd)-space shell model calculation.

With the successful advent of the ECR source at the 88-Inch Cyclotron, it is possible to investigate fragmentation reactions as a "higher yield" source of proton-rich nuclei very far from stability. The magnetic spectrometer in cave 4C and its focal plane detection system have been used for encouraging but still preliminary studies of the yields of such nuclei produced via ^{36}Ar reactions on a calcium target.

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Heavy Element Radiochemistry

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The group uses all three of the LBL accelerators to produce and characterize new elements and isotopes, to study nuclear reaction mechanisms, and to train students in modern nuclear and radiochemical techniques. Currently, research is focused on:

1. Synthesis and identification of new isotopes and elements in the actinide and transactinide region, along with attempts to synthesize superheavy elements;
2. Study of low-energy heavy ion reaction mechanisms such as massive transfer, complete fusion and deep inelastic scattering; and
3. Characterization of the mechanisms operating in intermediate energy (10–100 MeV/nucleon) and relativistic (≥ 250 MeV/nucleon) heavy ion reactions through studies of the target fragment yields, energies, angular distributions, etc.

Light ($A < 25$) heavy ion reactions with heavy actinide targets have been used at the 88-Inch Cyclotron to investigate "transfer" reactions to produce neutron-rich actinides. A comparison of actinide yields for the projectile pairs oxygen-16 and 18, neon-20 and 22 and calcium-40 and 48 has been made. The group is trying to understand the mechanism of these reactions by systematically measuring the variation of product yields, energies, angular distributions, etc. with projectile and target mass and energy. Studies are being extended to odd-proton target nuclides such as ^{237}Np and ^{249}Bk .

Members of the group have also used the 88-Inch Cyclotron, the GANIL accelerator, the MSU superconducting cyclotron and the SC synchrotron at CERN to study intermediate energy heavy ion reaction mechanisms. In particular, they are concerned with studies of the target fragment yields, energies, and angular distributions in light ion-heavy target reactions.

Research at the SuperHILAC has been directed toward the use of deep inelastic transfer and "cold fusion" processes to produce new isotopes or elements and to obtain an understanding of the mechanisms involved. Reactions of Kr and Xe projectiles with heavy actinide targets such as ^{248}Cm and ^{249}Cf have been investigated. Comparisons of above and below target yields are being made.

Research on target fragmentation at the Bevalac has involved single particle inclusive survey measurements of the angular, mass and charge distributions of the target fragments from the interaction of heavy relativistic ions with heavy targets. Radiochemical studies of limiting fragmentation and the possible formation of a quark-gluon plasma are planned for the future at ultra relativistic heavy ion accelerators. An international collaborative radiochemical search for anomalous is also being pursued at the Bevalac and other accelerators.

Collaborative preliminary studies with LLNL, LANL, and ORNL have shown the feasibility of the proposed Large Einsteinium Activation Program (LEAP). Cross sections for production of new neutron-rich isotopes appear favorable and chemical and nuclear studies of lawrencium isotopes have been initiated.

New Element and Isotope Synthesis

The research program of the Heavy Element Research group is now focused around LEAP (Large Einsteinium Activation Program). This program, although approved by a national review committee, has not yet been funded; however, a limited amount of Director's Funds has been allocated to allow interim research so that the program is proceeding, though at a slow pace. As before, graduate students continue to play an important role in it while simultaneously being trained in experimental techniques of nuclear physics.

A vital tool for exploration in the heavy element region was SASSY, our gas-filled magnetic separator. With a heavy target such as ^{254}Es , however, only relatively light heavy ions are needed for producing new nuclides and this condition results in broad angular distributions of the recoil fragments when they are emitted in such reactions. SASSY was completely unsuited for such experiments because of its 4-meter length and its small admittance, so we have designed a suitable replacement which we call SASSY II. Since funds (estimated at \$250,000) were not made available to build the instrument in the "normal" way using trained engineers, technicians, and the shops, we adopted the very unusual procedure of doing 95% of the work ourselves. As of October 1985 we have almost completed the job and SASSY II should be ready for testing soon. We calculate that we should obtain an overall efficiency greater than 50%, high enough to make it possible to look for element 110 in the $^{209}\text{Bi} + ^{59}\text{Co}$ reaction.

Another major research tool of the New Element and Isotope Synthesis Group is the On-line Apparatus for SuperHILAC Isotope Separation (OASIS). Recoils from heavy-ion-induced nuclear reactions are stopped in a tantalum catcher, which is kept at a temperature just below its melting point inside an ion source. The recoils diffuse out of the catcher, are ionized and then accelerated to an energy of 50 keV. An analyzing magnet selects isobars and focuses them onto various detectors. The beam of isobars can also be guided to a shielded room 4 meters above OASIS where low-background proton-, α -, $\beta^\pm$ -, γ - and x-ray experiments can be carried out. A fast tape system transports the selected isobars within 200 ms to a detection system that consists of a high purity Ge detector for $\beta^\pm$ and x-ray spectroscopy, and two n-type Ge detectors for γ and x-ray measurements. A $\Delta E/E$ telescope placed in front of one of the Ge detectors identifies charged particles, and a plastic ΔE detector in front of the n-type Ge detector distinguishes between γ - and β - radiation. One of the "Gamma-X" detectors is particularly well-suited, because of its large size (52%), to the measurement of high energy γ -rays from the decay of nuclei far from beta stability.

During this report period most of the physics with OASIS was focused on the synthesis and study of new, neutron-deficient nuclei in the rare-earth region. Several new beta-delayed proton emitters were discovered and their proton spectra, half-lives and, in some cases, their ground state spins were measured as discussed in a separate contribution to this report.

Of particular interest have been beta-delayed proton emitters with 81 neutrons that decay to highly excited, *magic* nuclei ($N=82$). The experimental beta-

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delayed proton spectra show sharp “peaks” that are quite distinct from the usual statistical spectra characteristic of the high level densities in this region. This indicates that in $N=82$ isotones significantly reduced level densities exist even at excitation energies of 4 to 5 MeV; a phenomenon that is usually only observed in much lighter nuclei.

By combining an improved statistical model with measured proton spectra we have been able to extract experimental β -strength functions and compared them for different theoretical models. One of these is a large-basis shell model resident on a CRAY X-MP. In collaboration with K. Takahashi and G.J. Mathews from LLNL we have recently completed calculations of the Gamow-Teller transition matrix elements for one of the $N=81$ isotones using this model and found excellent agreement with experiments. This gives us confidence that β -delayed proton spectra can be used to obtain β -strength functions for nuclei far removed from stability. In the deformed region where the above model becomes unworkable we have found that a Nilsson model with random phase approximation developed by Krumlinde and Möller is a valuable tool in the interpretation of experimental β -strength functions. In the future we hope to combine OASIS with a second, independent method, based on total absorption γ -ray spectroscopy, to measure β -strength functions of nuclei near the proton drip line.

Nuclear Astrophysics and Fundamental Symmetries

Ours is a new experimental group based at the 88-Inch Cyclotron. We are involved in a number of experiments in two distinct, but not unrelated, areas: 1) nuclear astrophysics and 2) tests of fundamental symmetries. In the area of astrophysics we are currently investigating a number of current problems in the nucleosynthesis of the heavy elements. Experiments in this area include studies of the β -decays and/or electromagnetic decays of specific nuclei of astrophysical interest. In addition, we are involved in the measurement of cross sections for a number of important proton and alpha-particle induced reactions. Specific studies include:

1. Positions and decay modes of excited states in ^{148}Pm and their relevance for determining the s-process neutron density.
2. Beta decays of ^{180}Lu and $^{180}\text{Hf}^m$ and their significance for the nucleosynthesis of ^{180}Ta .
3. Measurements of γ -ray production cross sections from proton and alpha-particle induced reactions required for γ -ray astronomy.

Under the heading of fundamental symmetries, we are involved in several different tests of conservation laws. We attempt to use nuclei as laboratories for testing fundamental interactions. Specific studies include:

4. Searches for the double beta decays of a number of different nuclei
5. Improved tests of the exponential decay law
6. Search for neutrino oscillations (LAMPF E645)

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Nuclear Structure Studies at High Angular Momentum

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During the past year the full 21 Compton-suppressed Ge detectors of the Berkeley array have been brought into operation and have performed as expected. A number of experiments have been done as these modules arrived (one per month); a first paper on ^{156}Er has been published [P.R.L. **54**, 2584 (1985)] and a second one on ^{158}Er has been submitted. These represent the start of a series of discrete-line studies in rare-earth nuclei which push to still higher spins, in order to observe how angular momentum is carried at these high spins (whether in collective motion or aligned single particles, or both). Also of interest is how the pairing correlations are quenched, and what shape changes occur. In these two studies the occurrence of the theoretically predicted band terminations has already been seen, as well as separate fast and slow feeding components into the top of the yrast cascade for ^{158}Er . Studies of ^{150}Dy and ^{148}Dy are being prepared for publication and work on several other nuclei is going on.

By the nature of the decay cascades, such discrete-line studies sample mainly states near and along the yrast line; these become very weak at high spin where most of the population is spread over the very high density of states ranging from 1–10 MeV above the yrast line. So to learn about the majority of the transitions at high spin and about the nature of the states themselves, we must develop techniques to study the continuum spectra and any structure present in them. An important shape change under investigation is the possibility of superdeformation in the nuclei near $Z=64$, $N=82$ at high spins; this has been observed in ^{152}Dy by the Daresbury workers, but should occur in other nuclei also, and it would be very desirable to measure the lifetimes of the transitions among the superdeformed states if this proves possible.

An important feature of the γ - γ correlation spectra that have been obtained by various groups in trying to study the continuum is that the valley along the diagonal in the $E_{\gamma_1} - E_{\gamma_2}$ plot, as well as the ridges that border it, are not very marked, amounting to only 5–15% effects. This is very different from what is expected of a simple rigid rotor. Since the few lifetime measurements that have been made in the continuum indicate that the average transition in the 0.75–1.25 MeV range (in rare earth nuclei) is very fast and collective, how can the weak ridges and filled-in valley be explained? A possibility is that for states well above the yrast line the high level density means a high degree of mixing. This can lead to collective transitions, but with a distribution of energies from a particular spin state (i.e., a “spreading width”). Techniques for measuring these widths are being investigated. A first experiment with NaI detectors gives average spreading widths of 50–150 keV for transitions around 900–1200 keV, along with a second much wider distribution. The use of Compton-suppressed Ge detectors and refinements in the methods should give better results and a clearer picture during the next year or so. Such studies together with Doppler line shape lifetime measurements in the continuum will play an increasingly larger role in the work of the group in the coming year.

Heavy-ion Reactions at Intermediate Energies

Nuclear reactions induced by heavy ion projectiles undergo pronounced changes in the region of bombarding energy between the Coulomb barrier (about 5 MeV/nucleon) and the Fermi energy (about 35 MeV/nucleon). The process of complete fusion of the projectile with the target exhibits such a change at about 7–8 MeV/nucleon. At this energy the observed average velocity of fusion residues begins to decrease from the center-of-mass velocity, an effect that indicates the onset of incomplete momentum transfer and incomplete fusion. As the bombarding energy increases, the cross section for complete fusion continues to decrease until there is little, if any, of this reaction mechanism left at the Fermi energy. Changes also occur in the characteristics of projectile-like fragments arising from peripheral reactions. The distribution of the velocities of these fragments about the average value increases rapidly in width and the average velocity falls below the velocity of the beam. One also finds an increase in the number of high velocity protons and alpha particles in the forward direction.

The decrease in the ability of nuclei to hold together (fusion) and the increasing tendency for them to appear in smaller pieces (break-up) as the bombarding energy is raised is qualitatively understandable in terms of the binding energy of nucleons and nuclear clusters, and the competition between the repulsive Coulomb force and the attractive nuclear force. As the available kinetic energy increases beyond these characteristic binding energies, and the average translational velocity of nucleons in the projectile becomes comparable to the maximum instantaneous velocity of nucleons found in the target nucleus, breakup or fragmentation processes must increase.

A quantitative phenomenological understanding of the mechanisms responsible for the outcome of a nuclear reaction in terms of the basic binding energies, decay thresholds, nuclear forces and nuclear structure is the goal of our group's experimental research in this intermediate energy region. Through a variety of experiments that exploit particular kinematical aspects of the reaction, we try to gain a deeper insight into the dynamics of the collision. The 88-Inch Cyclotron, with its new ECR ion source, is an ideal accelerator for studying this energy region since it can provide energies up to 35 MeV/nucleon for projectiles as heavy as neon and 20 MeV/nucleon for argon beams. In the following we give an overview of our work in this area, which is described in eight individual contributions to this annual report.

The identification of reactions in which only a target-like fragment (TLF) and a projectile-like fragment (PLF) are present in the final state has been accomplished with the Plastic Box. This is a 4π detector capable of detecting light charged particles (mostly protons and alpha particles) in coincidence with a PLF observed in a trigger telescope. With this device we studied the reactions of ^{20}Ne at 11 and 17 MeV/nucleon on a ^{197}Au target. The ratio of events with no light charged particle present ($S = 0$) to events having one ($S = 1$) or more was measured for PLFs varying from Ne to Li. It was also possible to infer the primary fragment's identity in the case of an $S = 1$ event by assuming that the excited

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fragment decayed by the charged particle channel with the lowest separation energy. These reconstructed primary distributions are compared to the prediction of two phenomenological reaction models. The probability that a primary fragment is emitted in a bound state is called the survival fraction. These values were found to be quite large, indicating that the excitation energy of the PLF was, on the average, quite low. The consequences of this in terms of nuclear models are discussed in the a contribution to this report.

In order to measure the excitation energy of a primary fragment excited above the threshold for charged-particle decay it is necessary to measure the identities, angles and energies of the two decay products. The detection of the light particle was accomplished with position-sensitive plastic-scintillator telescopes developed by our group. With this device we verified the reconstructions inferred in the Plastic Box experiments and, furthermore, determined the distribution of excitation energy as a function of charge and mass flow in the reaction. Here it is seen that the excitation energy in the target-like fragment correlates in first order with the amount of charge transferred and in second order with the number of transferred neutrons.

The measurements of relative kinetic energy of the PLF and the light particle indicated that the decay of the primary fragment is predominantly sequential rather than prompt. The relative importance of sequential decay and prompt fragmentation is a question of general importance in the study of the decay of complex nuclei. With the availability of the higher energy beams from the ECR source we decided to search for indications of a prompt decay. The method we chose was that of Shotter *et al.* and consists of a precise measurement of the relative kinetic energy in a region that contains no excited states and, therefore, no sequential decay. This experiment, using a 27 MeV/nucleon ^{16}O beam, also led to the observation of a particularly clean signature for the ($^{16}\text{O}, ^{17}\text{O}^*$) neutron pickup reaction to unbound states of $^{17}\text{O}^*$.

The use of transfer and break-up reactions to study nuclear structure was begun using beams of ^{20}Ne and ^{24}Mg from the ECR source and employed the solid state position sensitive telescopes used several years ago by our group for studying ^{16}O breakup. With these detectors very precise determinations of relative kinetic energy are possible. The study of the $^{20}\text{Ne} + ^{12}\text{C}$ reactions shows how an alpha particle may be transferred and reemitted via an excited state of the intermediate system. Only very specific intermediate states, characterized by high spins and α -particle cluster structure are populated in these transfer reemission reactions. Both transfer to the projectile ($^{20}\text{Ne} \rightarrow ^{24}\text{Mg}^* \rightarrow ^{20}\text{Ne} + \alpha$) and from the projectile ($^{20}\text{Ne} \rightarrow ^{16}\text{O}^* \rightarrow ^{12}\text{C} + \alpha$) have been observed.

The same experimental arrangement was used to search for the famous $^{12}\text{C} + ^{12}\text{C}$ molecular states in ^{24}Mg . The method used a 15 MeV/nucleon ^{24}Mg beam and a ^{12}C target, i.e., reverse kinematics, and a precise measurement of the relative kinetic energy of the two ^{12}C nuclei having approximately the beam velocity. The experiment was very successful, both from the operations standpoint (a steady beam for 15 shifts) and the functioning of the apparatus. A contribution in this report shows the high energy resolution and clean separation of the events

in which the three ^{12}C nuclei emerge in their bound states. Clear evidence for non-statistical nuclear structure effects in the decay of ^{24}Mg to two ^{12}C nuclei was found.

Fig. 1. Most of our group's experiments are carried out in the 60-Inch Scattering chamber of the 88-Inch Cyclotron. Several of the position-sensitive phoswich scintillator detectors are shown mounted for testing. In the foreground, left to right, are Janusz Wilczynski, Bernard Harvey and Krystina Siwek-Wilczynska. In the rear are Efrain Chavez, Hans-Rudolph Schmidt, Stuart Gazes, Yuen-dat Chan and Robert Stokstad.

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Deep Inelastic Reactions and Highly Excited Compound Nuclei

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Our recent work has been directed partly toward completing our understanding of angular momentum and energy transfer in deep inelastic reactions and partly toward elucidating the mechanisms of compound nucleus decay and complex particle emission both at low and high energy.

In the reaction $^{80}\text{Kr} + ^{174}\text{Yb}$ at 684 MeV/nucleon, we have observed the discrete gamma ray lines associated with both the heavy and the light partner as a function of Q value. By determining the Q value interval over which the lines of a given even-even isotope are replaced by the corresponding lines of the next even-even isotope with two less neutrons, we have been able to determine the excitation energy partition between the two fragments as a function of Q value. More energy than predicted from equilibrium conditions seems to be deposited in the light fragment, in agreement with recent dynamical theories on energy transfer.

At the same time the gamma ray line anisotropy has been studied as a function of Q value. An early rise of the anisotropy, suggesting prompt spin alignment presumably due to transfer reactions, is followed by a decrease and in turn by a new increase of the anisotropy until at the largest Q values isotropy is again attained. This behavior is understood in terms of the interplay between the spin fed to the fragments, and the thermal excitation of angular momentum bearing modes, which eventually manage to misalign the spin entirely at the largest Q values.

The theme of low energy emission of complex fragments has been developed with the intent of certifying it as a bona fide compound nucleus process. To this end we have studied the excitation functions associated with individual fragments in the reaction $^3\text{He} + \text{Ag}$ from just above the barriers up to 130 MeV of total excitation energy. The rapid rise of the excitation functions with energy quantitatively confirms the compound nucleus hypothesis and allows one to obtain the individual conditional barrier heights. Strong finite range effects predicted by modern versions of the liquid drop model are verified in detail.

The dependence of the potential energy vs mass asymmetry has been studied by means of reverse kinematic reactions like ^9Be and ^{12}C targets + ^{74}Ge , ^{93}Nb and ^{139}La projectiles. Complete charge distributions and kinetic energy distributions show that the fragments are emitted isotropically and with Coulomb-like energies as expected from compound nucleus decay and that the potential energy is the dominant factor, together with the temperature, controlling the yield of individual fragments. Effects due to the Businaro-Gallone point are clearly exhibited.

In more fissile nuclei, one expects that complex fragments would be emitted as a tail end of the standard fission mass distribution. We have shown that products with atomic numbers less than 20 in the fission of ^{244}Cm are in fact arising from binary division rather than being associated with an alleged ternary fission.

This appears quite clearly in the reverse kinematics reaction $^{12}\text{C} + ^{232}\text{Th}$. Possible modulations of the charge distribution due to shell effects may be studied in this way.

The origin of complex fragments at higher energies has been variously associated with undocumented processes like liquid vapor equilibrium, shattering or other multifragment processes. We found it profitable to utilize reverse kinematics reactions like ^9Be and $^{27}\text{Al} + ^{93}\text{Nb}$ at energies ranging from 20 to 40 MeV/nucleon. In these reactions, incomplete fusion creates highly excited nuclei that move forward with high velocity. It appears that complex fragments arise almost entirely from the binary decay of such highly excited compound nuclei. The two kinematic solutions associated with the isotropic decay in the center of mass with Coulomb-like energies are readily observed and provide a direct measure of the momentum transfer and of the Coulomb splitting. Coincidence measurements verify the binary mechanism and confirm that the sum of the charges is nearly independent of the asymmetry of the decay and close to the Z value of the incomplete fusion product after evaporation is accounted for. These compound nuclei are characterized by a temperature and a mean excitation energy per nucleon approaching the mean nucleon binding energy. It is expected that a great deal can be learned about the stability of nuclei at high excitation energy, in particular about the effect of high temperature on size and surface energy as well as about the modes of decay.

In this series of experiments we have demonstrated the pervasive nature of complex fragment emission from compound nuclei. Clearly any other novel mechanism of production has to deal with the coexisting compound nucleus mechanism as background. In fact, the expected onset of multifragmentation at even higher excitation energy may very well be dominated by a series of sequential binary decays.

The primary diagnostic tool for the mechanism of multifragmentation is the excitation function of binary, ternary, quaternary, etc, decays. We are planning to study these excitation functions in reverse kinematics reactions by means of a checkerboard detector. Each element is envisaged as a stack of position-sensitive silicon detectors and plastic scintillators. In such a device all the fragments are detected and their energy, position and charge determined. The excitation functions discussed above should be readily obtained with a minimum of analysis and simple gates can be readily set. For the moment we have performed extensive calibrations for the plastic scintillators in energy and charge ranges unavailable in the literature.

On the theoretical side, we have begun studying in some detail the process of incomplete fusion that seems to be prevailing at intermediate energies. The dynamical parameters, such as the potential energies associated with the creation of new surfaces and the relevant masses are incorporated into a general theory that predicts the thresholds of incomplete fusion in energy and impact parameter as well as the exit channel velocity of the ensuing products.

Elaborating on a speculation by Aichelin and Huefner that multifragmentation is a kind to the shattering of a brittle object, we have extended the theory to include the constraints of a fixed amount of created surface. A possible connection between the potential energy associated with the new surface and the fragment kinetic energy through the virial theorem is being investigated.

Relativistic Nuclear Collisions: Interactions in Emulsions

The Relativistic Heavy Ion Group's experimental program employs nuclear emulsion visual track detectors to carry out studies on the interaction of relativistic nuclei in matter. At the Bevalac, experiments on the interaction properties of relativistic ^{238}U nuclei in matter are in progress, emphasizing the kinematics of fission reactions and the topological characteristics of high-multiplicity ^{238}U -nucleus interactions. The second phase of Bevalac Exp #730H on the range-energy, energy loss and effective charge of high-Z nuclei ($E \leq 150$ MeV/nucleon) in stopping material has been completed. This experiment addresses key questions pertinent to heavy-ion inertial fusion. In collaboration with the University of Minnesota and UC Space Sciences Laboratory, experiments using 900 MeV/nucleon Au and Fe nuclei to study the higher order, relativistic corrections to the theory of energy loss of high Z nuclei was carried out.

As preparation for the forthcoming major collaborative CERN Exp. #EMU01 on particle production and nuclear fragmentation in collisions of ^{16}O beams at 50 and 225 GeV/nucleon, prototype emulsion chambers were irradiated by ^{16}O and ^{54}Fe beams at the Bevalac and evaluated. Results of this work confirmed that the experimental objectives of EMU01 can be fully met. This experiment includes groups from Berkeley, Jammu, Jaipur, Lund, Ottawa, Seattle, and Tashkent. The impetus for this experiment comes from theoretical estimates that suggest the possibility of a phase transition to a quark-gluon plasma (QGP) at these energies. Such a transition could be favored by large nuclear stopping power, with signatures being large values of pseudo-rapidity densities and their fluctuations. Use of nuclear emulsion stacks and emulsion chambers will provide the necessary spatial resolution to detect the expected signals even at the highest predicted particle densities. The Interactive Computer Assisted Measuring System (ICAMS), the data acquisition and measurement instrument will be an important asset in the measurement and analysis of this experiment.

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Relativistic Nuclear Collisions: Nucleus-Nucleus Collisions

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All this group's offices and equipment are located in Birge Hall on the UCB campus, which makes it easy to attract new students but restricts to some extent interaction with Nuclear Science Division staff. Current research falls into the following six principal areas:

1. Systematics of radioactive decay via emission of heavy ions such as ^{14}C , ^{24}Ne , and ^{34}Si (DOE support);
2. Search for highly ionizing particles in e^+e^- annihilation (TRISTAN experiment, supported by NSF) and in $\bar{p}p$ annihilation (Fermilab experiment, NSF support);
3. Cosmic-ray astrophysics (NASA and NSF support)
 - a. Final engineering design and construction of instruments for a 50 m^2 detector for a two-year space exposure starting May 27, 1987;
 - b. Construction of an experiment to detect anti-iron nuclei in cosmic rays at a level 3×10^{-7} of iron (in collaboration with Indiana University and the University of Michigan)
 - c. Construction of a balloon-borne magnetic spectrometer to measure the energy spectrum of antiprotons at $E < 1\text{ GeV}$
4. Search for grand-unification magnetic monopoles (NSF support)
Use of mica detectors at sensitivity $\lesssim 10^{-19}\text{ cm}^{-2}\text{ sr}^{-1}\text{ s}^{-1}$;
5. Ultrarelativistic nucleus-nucleus collisions (DOE support)
 - a. 200 GeV/nucleon ^{16}O collisions at CERN (1986)
 - b. 15 GeV/nucleon ^{32}S collisions at Brookhaven (1986).
 - c. Detector response as a function of Lorentz factor.

Relativistic Nuclear Collisions: Radioactive Beam Study and Light Particle Emission Study

Our group has been studying high-energy heavy-ion reactions at the Bevalac in a collaboration between the Institute for Nuclear Study (INS), the University of Tokyo, Osaka University, and LBL. The experimental program of the group emphasizes two types of measurements, one measures the interaction cross section (E690H) and magnetic moments (E732H) using beams of radioactive nuclei, and the other measures light particle emissions ($\pi^\pm$, p, d) from heavy-ion collisions (E593H, E733H).

In experiment E690H, interaction cross sections between two nuclei were measured using beams of ${}^{3,4,6,8}\text{He}$, ${}^{6,7,8,9,11}\text{Li}$, and ${}^{8,10}\text{Be}$ at 790 MeV/nucleon. Beams of radioactive nuclei were produced through the projectile fragmentation of 800 MeV/nucleon ${}^{11}\text{B}$ and ${}^{20}\text{Ne}$. Separation of the nuclei were made using a magnetic analyzing system of the Bevalac beam line (B-42). After the separation of the secondary beam, interaction cross sections were measured using the HISS spectrometer. Root-mean-square matter radii of He, Li and Be isotopes were deduced from the interaction cross sections using a Glauber-type calculation. Appreciable differences of radii among isobars (${}^6\text{He}$ - ${}^6\text{Li}$, ${}^8\text{He}$ - ${}^8\text{Li}$, and ${}^9\text{Li}$ - ${}^9\text{Be}$) were observed for the first time. The nucleus ${}^{11}\text{Li}$ showed a remarkably large radius suggesting a large deformation or a long tail in the matter distribution. The experiment is being extended to all p-shell nuclei.

A new experiment E732H has been planned to determine nuclear moments of unstable nuclei in the $f_{7/2}$ shell. For this purpose an NMR method will be applied to short-lived β emitting nuclei produced through the projectile fragmentations. Test runs have already begun in Bevalac beam line B-44 to confirm the separability of isotopes. Major parts of the experimental apparatus necessary for the NMR measurements have been designed and built.

Experiment E593H measured pion spectra at 0° in coincidence with heavy fragments emitted at the same angle for studying Coulomb distortion effects on pion spectra. The experiment was performed at HISS using a La beam of 800 MeV/nucleon, and the data analysis is in progress. A prominent peak has been observed in the π^- spectrum at around the projectile velocity. The peak position shifts to lower momentum for smaller impact parameter, and this shift is thought to be due to larger friction in collisions of smaller impact parameter. The distribution of the projectile fragment sum charge has been measured in the La + C reaction. The results indicate that a transverse growth of the cascade has a large effect in the reaction.

The projectile- and target-mass dependence of light particle production in heavy ion collisions has been studied by measurements of pions and light nuclear fragments (p, d, t, ${}^3\text{He}$, and ${}^4\text{He}$) in La + La collisions at 800 MeV/nucleon (E733H). A magnetic spectrometer was used for detection of these particles and a set of 120 multiplicity counters was used for event selection. We have measured (a) energy spectra, (b) angular distributions, (c) the pion to nucleon yield ratio, and (d) the coalescence relation for the formation of composite fragments in both

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low- and high-multiplicity events. By comparing these results with the previous data for lighter mass collisions, we have found that both pion yield and pion kinetic energy are greatly influenced by the final state interactions.

a

Relativistic Nuclear Collisions: Pion and Correlation Studies

The Berkeley research activities of our group center mainly on the study of charged pions or correlated pairs of particles produced in high-energy heavy-ion collisions at the Bevalac. The technical approach involves a large (~ 4 meter flight path) dipole-dipole magnetic spectrometer (JANUS) and combinations of fast scintillators and wire chambers interfaced with a CAMAC-VAX 11/750 data acquisition system.

A major part of our research effort involves pion interferometry studies. In the past ten years theorists have predicted that exotic phenomena such as pion condensation and quark-gluon plasmas occur in relativistic heavy-ion collisions. One way to obtain information about these phenomena is to measure the radius, lifetime and coherence of the pion-emitting source produced in the collision. The Hanbury-Brown/Twiss effect, which has been used extensively in astronomy to measure the radii of stars, provides a direct method to measure these pion source parameters. In practice, we measure the momenta ($\vec{p}_1$ and $\vec{p}_2$) of coincident like-charged pions in our spectrometer and, using the two pion yields thus obtained, form the correlation function $C(\vec{p}_1, \vec{p}_2)$. This experimental correlation function is then fitted to a model, which assumes a Gaussian space-time distribution for the sources, and the source parameters are extracted. Thus far we have used this technique to measure source parameters for the systems 1.8 GeV/nucleon ^{40}Ar on KCl, 1.8 GeV/nucleon $^{20}\text{Ne} + \text{NaF}$ and 1.7 GeV/nucleon ^{56}Fe on Fe.

In addition to our experimental program in pion interferometry, we are also carrying out theoretical studies based on this method using the intranuclear cascade model (INC). For a given projectile-target system, the INC generates pions of known momentum and known position and time of creation. This information allows a symmetrization to be performed on pions from the same event, which induces the Hanbury-Brown/Twiss effect in the INC. One then uses the same techniques that are applied to experimental two-pion pairs (i.e., form the correlation function and fit it with a Gaussian space-time distribution) to extract INC predictions for the pion source parameters. Reasonably good agreement has thus far been found between INC and measured source parameters.

Another part of the work is the determination of the inclusive or tagged cross sections (with an exploration of the angular dependence) for charged pion production in heavy-ion reactions. Our spectrometer is nearly unique for doing 0° and small angle pion spectroscopy at the Bevalac. The existence of both positively and negatively charged pions facilitates determinations of simple Coulomb effects and therefore the charge density evolution in heavy-ion collisions by observation of the π^-/π^+ ratio as a function of pion energy, bombarding energy, and target-projectile charges. In fact, we found that pions produced with low energy in the projectile frame have large π^-/π^+ ratios due to the Coulomb fields of the projectile fragments. Systematic observations of the sharp anomaly were made to compare with various models for production.

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Substantial progress was made in the analysis of the muon catalyzed dt fusion experiment performed in 1983 and 1984 at SIN. In runs using a liquid target we measured cycling rates exceeding 10^8 per sec, suggesting that a single muon can initialize more than 100 dt fusions or an energy equivalent of about 2 GeV. In the experiments at low density [See Phys. Rev. Lett. **53**, 1137 (1984)] even larger fusion rates were observed. In combining the data sets we discovered a very surprising density effect (See Fig. 1).

Future work that our group intends to pursue will utilize the experimental techniques and apparatus that we have built. The availability of Bevalac beams of the heavier elements (Au, Pb, or U) will allow new pion spectroscopic measurements to search for evidence of highly compressed nuclear matter effects through the pion interferometry method.

A search for pineuts ($n\pi^-$ bound to a cluster of $\sim 2n$ neutrons) has been started. The experiment will be performed with the JANUS spectrometer and will be sensitive to particles with a lifetime of the order of 10 ns or longer. The sensitivity to the production cross section for $(\pi^-)^2n^4$ is estimated to be of the order of $10^{-34} \text{ cm}^2 (\text{MeV/c})^{-1} \text{ sr}^{-1}$ assuming 100 hours of data taking with an ^{40}Ar beam at an intensity of 10^9 particles/pulse on a uranium target.

Now that heavy elements can be accelerated at the Bevalac, there are new opportunities in atomic physics. Our earliest Bevalac work involved measuring K x-ray production cross sections. With Stanford collaborators we have measured extensively the x-ray spectra from 190 MeV/nucleon Xe ions and 375 MeV/nucleon U ions. We observed not only target and projectile x-rays but also the radiative electron capture peak. We are relating the results to aid work in heavy ion inertial fusion. We are also collaborators with the Heckman group on stopping-power studies of Au ions at 50 and 150 MeV/nucleon in support of inertial fusion research and development.

Various members of the group are involved in collaborative work centered at other laboratories, such as muon and pion experiments at TRIUMF.

Fig. 1. Muon catalyzed fusion: observed cycling rates λ_C^N (= repetition rates for the $d\mu t \rightarrow \alpha + \mu + n$ fusion cycle) normalized to liquid ${}^1\text{H}_2$ density (=1) versus tritium admixture C_T show a pronounced density effect.

XBL 8510-4313

Relativistic Nuclear Collisions

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Several experiments completed this year represent collaborations between the above-listed personnel and research groups from other universities, notably Johns Hopkins University (L. Madansky, T. Hallman), Northwestern University (D. Miller, F. Luehring) and Louisiana State University (P.N. Kirk, J.F. Gilot).

The main topic of research by this group is the study of nuclear matter in relativistic heavy ion reactions. Our work has concentrated on the use of unusual probes or the detection of rare signatures to shed light on the state of hadronic matter reached during these collisions.

Our major experiment completed this year was the measurement of the single direct electron to charged pion ratio as a function of transverse momentum for the $p + \text{Be}$ system at $E_p=2.1$ and 4.9 GeV. Previous measurements of this ratio demonstrated nearly universal behavior for bombarding energies in the range $10\text{--}300$ GeV. At large p_T the ratio of single electrons to pions is approximately 10^{-4} but rises rapidly as p_T decreases below about 1 GeV/c. On the other hand, there is no evidence for direct lepton production at bombarding energies lower than 800 MeV at the 10^{-6} level. This work, then, bridges an important gap in the data.

Our results confirm this universal behavior down to 2.1 GeV. We observe in particular a dramatic rise in e/π with decreasing p_T and a high p_T ratio of $\sim 10^{-4}$. Monte Carlo calculations which model both lepton and pion production through the isobar model indicate rough agreement of our results with phase space and isospin considerations. Preliminary results also predict a drop in the electron to pion ratio at fixed p_T by more than an order of magnitude when the bombarding energy is reduced from 2.1 GeV to 800 MeV. This result is also in agreement with the upper limits found in the low energy work.

In other heavy ion research we have also determined the energy spectrum of K^- from the reaction $^{28}\text{Si} + ^{28}\text{Si}$ at 2.1 GeV/nucleon. These kaons are "subthreshold" in the nucleon-nucleon center of mass system. This energy spectrum is approximately exponential in shape, with a slope corresponding to a temperature of 91 ± 7 MeV. Such a result rules out several models for kaon production, such as ϕ -bremsstrahlung or $K\bar{K}$ condensation, but is consistent with collective effects such as the presence of 6- or 9-quark bags or the enhancement of the strange sea quark density within nuclei.

During the K^- production measurement we carried out a search for fractional charge, rare long-lived particles, and subthreshold antiprotons. Upper limits ranging from one part in 10^4 to one part in 10^7 were set for exotic particles with masses in the region 0.5 to 4 GeV/c². One possible antiproton candidate was observed.

Further studies of both subthreshold kaon and antiproton production, as well as a more sensitive search for exotic particles, is continuing with the construction of a new spectrometer beamline (Beam 44). The new beamline incorporates many improvements over the old experiment. By shortening the time of

flight path one gains a factor of 10 due to kaon decay in flight. A further factor of 10 increase in acceptance is obtained by redesign of the detectors and magnetic elements. Data analysis is drastically simplified by the installation of ultra-fast scintillators and the development of efficient aerogel, gas, and liquid Čerenkov counters.

A preliminary run with this beam line shows that the resulting time of flight spectra are much cleaner than in the previous experiment. Pions and kaons were separated on-line at all momenta between 0.5 GeV/c to 2.0 GeV/c, while the rejection power of the Čerenkov counters (greater than 1 part in 10^5) discriminated eventually against all pions. Of the entire (preliminary) data sample of 100,000 events, 44 survived our Čerenkov vetos and time of flight consistency requirements. Of these, 26 have flight times consistent with kaons, 16 are unvetoesd pions, and two are "background" events. The remaining two events appear to be consistent with antiprotons and will be given further study.

Relativistic Nuclear Collisions: The Plastic Ball

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The group is a continuing collaboration between GSI (Gesellschaft für Schwerionenforschung, Darmstadt, West Germany) and LBL. The work of the group centers on the use of the Plastic Ball to study central collisions of relativistic nuclei with the aim of learning about nuclear matter at high temperature and density.

Collective flow of nuclear matter has been discovered by observation of the event shapes. Both bounce-off of the spectator matter and side-splash of the participant matter has been seen. The side-splash is taken as direct evidence of the production of high density nuclear matter. The data analysis is now concentrated on the quantification of the side-splash effect as a function of projectile-target mass and beam energy.

From the proton-proton correlations, the size of the emitting source has been obtained as a function of multiplicity and from it the thermal freeze-out density of an expanding fireball is deduced to be 25% of normal nuclear density. Values for the chemical freeze-out density and entropy have been deduced from the ratio of the deuteron yield to the proton yield as a function of multiplicity. The low entropy values are added evidence that compression takes place in the reactions.

Recently the *Mall* part (10 to 30 deg.) of the Plastic Ball was used to study fragments up to fluorine, while the *Outer Wall* (2 to 10 deg.) measured fragments up to carbon. The systems studied were 200 MeV/nucleon Au on Au and Fe targets. The goal is to learn about multifragmentation or the liquid-gas phase change. This work was a collaboration with the Harris group and a group from LANL.

Finally, preparations are well underway for an experiment at the CERN Laboratory's Super Proton Synchrotron (SPS) using 60 and 225 GeV/nucleon ^{16}O and ^{32}S beams. This is an expanded collaboration involving the University of Münster, Lund University and Oak Ridge National Laboratory.

Relativistic Nuclear Collisions: TASS/DLS

The Two-Arm Spectrometer System (TASS) consists of two fully rotatable magnets with accompanying scintillation hodoscopes and Čerenkov counters for particle identification. It was first operated in July 1980 and has served to measure two-particle correlations and single-particle inclusive spectra for subthreshold pions (La + La at 246 MeV/nucleon) and mid-rapidity pions (Ca + Ca at 1.05 GeV/nucleon). Most recently it has been used to measure the production of direct leptons ($e^\pm$) in high energy p-nucleus and nucleus-nucleus collisions (experiment 670H).

With the successful observation of direct leptons in 670H, TASS was decommissioned (Spring 1985), and a new, much larger aperture two-arm magnetic detector is being constructed by a collaboration involving Lawrence Berkeley Laboratory, Johns Hopkins University, Louisiana State University, Northwestern University, UCLA and Clermont-Ferrand. This system will have large scintillation hodoscopes, drift chambers, Čerenkov counters and a multiplicity array. The new spectrometer (See Fig. 1) is referred to as the Dilepton Spectrometer (DLS) and will be used to measure the mass spectrum of e^+e^- pairs up to $M_{e^+e^-} \leq 800$ MeV. It is generally accepted that leptons probe the hot, compressed phase of the collision process. The single $e^\pm$ s already observed by 670H must originate from e^+e^- production, the origin of which could be associated with quark-antiquark annihilation, $\pi^+\pi^-$ annihilation or hadronic bremsstrahlung processes in these collisions. The dilepton program of the DLS constitutes a major new thrust at Bevalac energies to understand the nature of nuclear matter under the extreme conditions of temperature and density. It is expected to continue at the Bevalac for several years. The possibility exists that the DLS could be reconfigured for dilepton studies at the AGS. This study is underway.

Fig. 1. Artist's conception of the Dilepton Spectrometer (DLS).

XBL 8512-9589

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The HISS facility consists of a large solid angle magnetic spectrometer designed to measure multi-particle final states produced in relativistic heavy ion collisions. The heart of the facility is a 7 Tm. superconducting magnet. It is surrounded by a variety of detectors which can be arranged in different ways to suit the needs of specific experiments. In addition to the local group listed here, users from INS-Tokyo, Michigan State University, Kent State University, U.C. Riverside and GSI-Darmstadt are active at the facility. During the period under review, progress was made in a variety of different directions.

Analysis of the ^{12}C break-up experiment (E513H) has continued. This experiment was designed to measure all the charged-particle final states that can be formed in the decay of this nucleus. The overall channel populations have been extracted and work is now beginning on the detailed study of specific channels such as $^{12}\text{C} \rightarrow 3\alpha$ and $^{12}\text{C} \rightarrow ^{11}\text{B} + p$.

Two other experiments ran at the facility during this period. The first (E690H) was designed to measure the interaction cross sections of unstable nuclear isotopes produced as secondary radioactive beams. This collaboration has now measured the cross section (and hence, indirectly, the radius) of all particle stable p-shell nuclei, including such exotic species as ^{11}Li and ^8He . The second experiment to run (E772H) has measured the cross sections and momentum distributions of isotopes produced by the fragmentation of ^{40}Ar , ^{93}Nb and ^{139}La beams. Data have now been taken for all three cases and are being analyzed. The results will be important for an understanding of the reaction mechanism as well as for the design of future secondary-beam experiments.

Development of new instrumentation is an important part of the work of the group. During the period under review, a new Čerenkov hodoscope was bought into use that allows simultaneous measurement of the charge and velocity of relativistic heavy ions to be made with very high precision. A prototype drift chamber was tested and construction began on a new $1.5 \times 2\text{m}$ chamber. This will be an important addition to the equipment available at the facility.

CBB 857-5183

Relativistic Nuclear Collisions: Streamer Chamber

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The Streamer Chamber allows the study of charged particles as well as K^0 and Λ^0 production over most of the 4π solid angle in high energy heavy ion collisions. Detailed 4π exclusive data are necessary to study the behavior of nuclear matter under conditions of extreme temperature and density. Up to now projectiles from protons to lanthanum have been used extensively in our experiments. It is planned to extend these studies to the heaviest elements.

Our group has upgraded the LBL Streamer Chamber to be able to use metallic targets, and has reduced the loading effect of the chamber voltage due to high energy delta rays from heavy projectiles. Instrumentation has been implemented to monitor the chamber performance with, among other things, an UV laser that produces tracks with a well-defined ionization. This has enabled us to optimize the streamer chamber parameters to obtain the most stable running conditions. A forward-angle 384-element scintillator array has been built to complement the streamer chamber particle identification capabilities in the region of momenta above 1 GeV/c and to enhance tracking capability in the forward direction. This detector array is calibrated and monitored using a light-fiber coupled N_2 laser.

Until recently total measurement of events has been carried out only at the semi-automatic PEPR facility at Heidelberg. At LBL data analysis has concentrated on scanning and on measurement of selected events such as Λ^0 or K^0 production. In the past year several major improvements have been achieved or initiated. At LBL digitizing tablets have been installed on the scanning tables, permitting image-plane measurement of the track coordinates, and on-line reconstruction in three dimensions of the track parameters using the program TVGP and a VAX computer. This method allows immediate remeasurement of tracks that fail. We are now carrying out complete event reconstruction using the new facility. At Marburg digitization of the complete event image on film has been carried out using a CCD scanning device. With an array processor plus some operator assistance it has been possible to reconstruct and measure total events. The Marburg facility is now in full operation for measurement of Bevalac data. A similar system is being constructed by Texas A&M University for application initially to 40,000 intermediate energy events recorded in experiment 557H at the Bevalac. A fully digitized data acquisition and analysis system is being developed by LBL for initial use in experiment NA35 at the CERN SPS (see below) and for later use at the Bevalac. This is the culmination of our more than five years of study of the capabilities of CCD cameras in conjunction with the LBL Streamer Chamber. Data will be acquired using high-resolution CCD cameras, obviating the use of film. The objective in data analysis is to make it completely automatic, though if difficulties arise it can be used in an advanced operator-assisted mode.

In addition to preparing for new Bevalac exposures and carrying them out, the analysis of previous experiments has continued:

- 400H This experiment used a proton beam and a backward angle trigger to investigate the systematics of backward going protons. The data are in the final stages of analysis.
- 401H This experiment measured Ar + KCl reactions between 0.4 and 1.8 GeV/nucleon, in central and minimum bias configurations. From these data, a study of π^- and charged multiplicity systematics has been made, and estimates of the nuclear compressibility as a function of density have been extracted. The pion and proton spectra at 1.8 GeV/nucleon have been explained in terms of isobar formation and decay, resolving a long standing puzzle. The production of Λ^0 at 1.8 GeV/nucleon has been measured, as well as the Λ^0 polarization. After reconstruction of all the charged particle tracks from each event, carried out using the semi automatic PEPR facility at Heidelberg we demonstrated collective flow and nuclear stopping. Analysis of these data by the new technique of transverse momentum analysis led to an independent estimate of nuclear compressibility, in agreement with that extracted from pion production. Measurement and analysis of this rich body of data is still in progress.
- 564H This experiment is a high statistics run on the $^{40}\text{Ca} + \text{Ca}$ reaction at 2.1 GeV/nucleon, aimed at obtaining an increased sample of Λ^0 production. The first scan of the data for Vees has been completed, and the results have been analyzed. A second scan is in progress, using a newly developed technique.
- 557H This experiment studied Ar + KCl and Ar + BaI₂ at energies between 30–90 MeV/nucleon, using image intensifier cameras to permit operation of the streamer chamber at lower voltages. A large sample of events was recorded; particle identification was tested using the ALICE system at ANL. Full measurement of the events is planned using the film digitizing system under construction at Texas A&M University.
- 629H This experiment focuses on interactions between heavier nuclei. An extensive set of data have been acquired for La + La collisions at energies between 0.4 and 1.4 GeV/nucleon. These involve, in addition to the streamer chamber, the 384-element forward detector which, by means of dE/dx and time of flight, identifies the particles in the projectile and forward participant regimes. Some preliminary results on π^- production have been presented, but final conclusions await correlation with data on the participants. Several hundred events have been fully measured at Heidelberg, and similar measurements have been started at LBL using the digitizing tablets. Further Bevalac runs have been approved for Au + Au and for $^{48}\text{Ca} + ^{48}\text{Ca}$, the latter to test the isospin dependence of the equation of state.
- NA35 This major experiment, at the CERN Super Proton Synchrotron, is a collaboration of the GSI-LBL Streamer Chamber Collaboration with groups from Athens, Bari, Freiburg, Krakow, Munich and Warsaw. It will use a large streamer chamber in a superconducting magnet to record and

measure all the charged tracks in each event, followed by extensive calorimetry to identify π^0 and to study the distribution of electromagnetic and hadronic energy in the forward hemisphere. Beams of ^{16}O , ^{32}S and possibly ^{40}Ca will be used at 60 GeV/nucleon and 225 GeV/nucleon. The LBL scanning and measuring facility will be devoted to analyzing the data from this experiment, with special emphasis on Λ^0 production. A major contribution being made by LBL is the streamer chamber supervision system. This uses two CCD cameras with 1024×1024 pixels each. The CCD pixels will be digitized to 8 bits and transferred in parallel to an on-line image processing system based on a VAXstation II computer (Micro-VAX II). Attached to this will be a 10 million-instruction-per-second integer coprocessor, the Mercury Computer Systems 3216, and peripherals. The primary function of the system is to provide quantitative analysis of the streamer chamber performance and event topology on line at CERN. Beyond this it is hoped to develop measuring techniques that will permit extraction of variables such as multiplicity or projected pseudo-rapidity for each event. After the NA35 runs, scheduled for late 1986 and Spring 1987, the system will be enhanced for image recording at the Bevalac.

Nuclear Theory

1. Hadronic and Quark Matter at High Energy Density

A major undertaking is the study of matter at high energy density, realized either by high temperature, or density, or both. This regime is of great interest since it impinges on both the fields of relativistic nuclear collisions, and the physics of neutron stars. At densities below the deconfinement threshold, matter can be discussed in terms of hadrons and their interactions, employing a relativistic effective field theory. Earlier work along these lines has included the study of phase transitions, abnormal matter, and hyperons in neutron stars. Current work includes the gas-liquid phase transition in nuclear matter, and dynamical paths for exploding nuclear matter following a high energy collision. Another line of work is concerned with the structure of nucleons, and recent developments of soliton models. There is some evidence (EMC effect) that even in normal nuclei, quarks may weakly manifest their presence, and certainly in high density matter this is expected. It is therefore of interest to explore ways of incorporating nucleon substructure into the theory of nuclear matter. There has been much interest in the last several years in solitons as representing non-perturbative solutions of QCD. We have been very interested in these developments because having a lagrangian that describes the internal nucleon structure, one can carry the theory a step further by constructing solutions in nuclear matter, and exploring how the internal properties of the individual nucleons are modified by their neighbors, and how in turn these changes are reflected in the properties of matter. This is of course a much more complicated nuclear many body problem than the one that is normally treated in nuclear physics, and we have made strong simplifying assumptions, such as a crystal structure for dense matter. Work on solitons is also being extended in another direction, by incorporating additional meson fields in an effective gauge theory and studying the stability of the solutions.

2. Nuclear Collisions at Ultra-Relativistic Energies

Quantum chromodynamics predicts the existence of a new phase of hadronic matter called the quark gluon plasma. That phase transition is expected to occur when the energy density exceeds the ground state energy density in nuclei by about an order of magnitude. A strong effort is underway in the theory group to calculate whether such energy densities could be generated in nuclear collisions at ultra-relativistic energies. In this regard we are studying the problem of nuclear stopping power and the space-time development of hadronization in high energy hadron-hadron and hadron-nucleus collisions. We have recently developed a parton cascade model that can account for the A dependence of baryon and pion inclusive yields at 100 GeV. Currently, we are studying the beam energy dependence of the energy loss of the leading hadron to be tested by upcoming data from AGS, CERN, and FNAL on pA collisions. Our calculations show that nuclear stopping power is perhaps large enough to bring uranium nuclei to rest in the center of mass system at energies up to ~ 50 GeV/nucleon. We have made predictions for nuclear collisions that will soon be tested at CERN using oxygen beams at 50 and 225 GeV/nucleon.

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At much higher energies, ≥ 1 TeV/nucleon, even the heaviest nuclei are not thick enough to stop each other. However, multigluon exchange could lead to the formation of large color electric field between the nuclei. We are studying such (Low-Nussinov) models to calculate how large the energy densities could get in the central rapidity regions. As the two nuclei pass through each other, they become “charged” to color nonsinglet states and act as color capacitor plates. However, the color fields produced between the nuclei are unstable with respect to pair production of quarks and gluons. We have recently calculated the pair production rates in covariant constant $SU(N)$ fields and are currently developing a chomo-transport theory that will allow us to follow the expansion of even non-equilibrium quark-gluon plasma. Current estimates indicate that energy densities up to 100 times that found in nuclei could thus be generated in a system with low baryon number.

We are also interested in the transport properties of quark-gluon plasmas near equilibrium. Using QCD phenomenology we have estimated the relevant scattering rates that control properties such as the viscosity and color conductivity. We have applied Navier-Stokes theory to the analysis of cosmic ray data and continue to follow with interest results from cosmic ray experiments. Macroscopic detonation and shock models have also been developed to explore what violent phenomena may result from the plasma to hadronization transition as the system expands. The problem of understanding this transition more microscopically is under investigation.

Finally, in this area we are working on what signatures could be best used experimentally in the search for and diagnostics of this new phase of matter. We continue to develop the theory of pion interferometry and have recently shown how the inside-outside cascade dynamics could be analyzed using this technique. We have studied strangeness production, and currently studying charm production as possible diagnostic tools. In this respect we interact closely with local experimentalists in helping to identify key experiments that may be needed.

3. Nuclear Collisions at Relativistic Energies

The theory group continues to enjoy close contact with experimentalists working at the Bevalac at LBL. The primary objective of this research is to extract the nuclear matter equation of state up to several times normal density and temperatures $\lesssim 100$ MeV. We work with a variety of theoretical methods (intranuclear cascade, hydrodynamic, and statistical models) to analyze the data. A necessary intermediate step toward our goal is the classification and understanding of the complex reaction mechanisms involved in nuclear collisions at these energies. For example the role of Coulomb effects and the Pauli principle must be separated from the role of mean fields and thermal fluctuations. This long program is now starting to bear fruits as we come closer to being able to extract from the volumes of data the sought after nuclear equation of state. We are entering a new era of high precision data that call for even more elaborate and reliable calculations.

Current problems of interest to our group in this area are composite formation and its relation to the entropy puzzle, the role of two body correlations in the nuclear dynamics, the role of mean fields and configuration dependent effective masses on transverse flow phenomena, and the relation between the apparent stiffness of the nuclear equation of state deduced from the nuclear collision data to the much softer equation of state needed in supernova calculations.

4. Nuclear Dynamics at Low Energy

Nuclear collisions of low energies produce, under suitable kinematical conditions, a transient system which may be called a dinucleus because of its distinct binary character. This unique manifestation of the nuclear many-body system has a rich dynamical structure which may be explored in damped nuclear reactions. We are continuing to develop our understanding of the dinuclear system as the quality and scope of the experimental data grow. In particular, the quantal foundation of the nuclear-exchange transport model has been solidified and application of the model to distant dinuclear configurations has been discussed. Certain aspects of the angular momentum dynamics have been further explored, in particular the tilting mode. An important new frontier is the transition between the dinuclear and mononuclear regimes which new data on the mass-asymmetry mode provide intriguing information.

In the mononuclear regime, the emphasis continues to be on the relation between the order-to-chaos transition in nucleonic motions and the character of collective nuclear dynamics. Evidence is accumulating for the validity of the prediction that, when the nucleonic motions are ordered, the nucleus as a whole should behave as an elastic solid, whereas when the nucleonic motions are chaotic, it should behave as a very viscous fluid, with a novel type of viscosity. The relatively simple chaotic regime collective dynamics continue to be confronted with a widening body of experimental data. In the ordered regime, the formula for the frequency ω of the nuclear giant quadrupole oscillation has been re-derived and expressed in the particularly simple form: $\omega = \sqrt{2}$ (Fermi velocity)/(Nuclear Radius). A comprehensive study is underway of the transfer of energy between a time-dependent container (the idealized nuclear potential) and an ideal, long-mean-free-path gas of particles representing the nucleons. Depending on the symmetries of the container and the nature of the time dependence, this transfer is observed to be elastic, visco-elastic or dissipative. These studies should help to illuminate the complex behavior of actual nuclei in the transitional region between the two simple limiting cases.

A number of other items of current interest include the generalization of some of the "Fermi jet" formulae to take account of the diffuseness of the nuclear potential and refinements in the theory of the radioactive decay by the emission of ^{14}C and other heavy particles.

5. The Macroscopic Approach to Nuclear Properties

A consistent application of the Droplet Model of nuclei to the problem of electric dipole moments in nuclei that have odd parity (octupole, etc.) components in their shape has raised some serious questions. Enhanced E1 transition rates in such nuclei seemed to indicate that the dipole moment should be somewhat larger than the values predicted by the charge redistribution in the bulk of the nucleus. However, we find that the contributions from surface effects, which are an important part of the Droplet Model, have a sign opposite to that of the bulk effects and tend to cancel them almost completely. This means that the interpretation of the E1 transition rates has to be reevaluated. The methods developed in these calculations for dealing with the contributions from the surface will also be useful in evaluating the corrections to be applied to the expressions for other multipole moments besides the dipole moment.

When the size of the system becomes comparable with the range of the force, as it does for light nuclei, there are new terms in the expressions for the central density (and binding energy) of a nucleus that are outside of the original formulation of the Droplet Model. We have used the “energy density approach” to investigate such terms, and one consequence of these studies is the realization that the corrections to the binding energy are of a higher order than those to the nuclear density distributions. The consideration of such “finiteness” terms continues with the goal of reformulating the macroscopic approach to include such effects. A preliminary study involving the inclusion of an empirical term in the Droplet Model mass formula that falls off exponentially with nuclear size has already resulted in a number of substantial improvements in the predictive power of the theory.

Isotopes Project

The Isotopes Project, as a member of the Nuclear Data Network (NDN), is responsible for the following:

1. Evaluating nuclear structure and decay data for mass chains $A=167-194$, and preparing the data for incorporation into the Evaluated Nuclear Structure Data File (ENSDF).
2. Producing the *Table of Radioactive Isotopes*, a reference book which contains adopted data on atomic and nuclear radiations, derived mostly from ENSDF.
3. Designing methods for the analysis of nuclear data, and developing the corresponding computer codes for use by the national and the international nuclear data networks.

During the past year, the group worked exclusively on the production of the *Table of Radioactive Isotopes*, to be published by John Wiley & Sons, Inc. in 1986. The book has been generated interactively with the LBL/VAX computers, using the database management system DATATRIEVE and the text processing code TROFF. This book demonstrates the application of modern computer technology to the analysis of massive amounts of data and to the on-line production of high quality output for publication. A useful by-product is an interactive computerized nuclear data bank, available in any of the computers of the Computing Division VAX cluster. This database contains numerical information from ENSDF, indexed for optimum usefulness and response time, and additional horizontal compilations, such as *The 1983 Atomic Mass Table* of Wapstra *et al.*, which may be accessed by remote users through the HEPnet (High Energy Physics Network), MILNET, and TYMNET computer networks.

Although the Isotopes Project did not evaluate data for ENSDF this past year, the evaluations of mass chains $A=171$ and 181 completed the previous year, were recently incorporated into ENSDF and published in *Nuclear Data Sheets*.

The Isotopes Project is represented on the Formats and Procedures Subcommittee of the U.S. Nuclear Data Network. This subcommittee meets every year, and establishes the formats and methods of analysis for nuclear data entered into ENSDF by the members of the national and international nuclear data networks. The physics checking computer code SPINOZA, produced by R.B. Firestone, has been recommended by the subcommittee and will be distributed to all the NDN centers shortly. The statistical treatment of constrained nuclear data, proposed by the Isotopes Project, has been accepted and a computer code that will be developed by E. Browne should be available in 1986, for general distribution to the nuclear data evaluating centers.

The Isotopes Project maintains an extensive collection of references, and provides data on request. It also subscribes to major nuclear physics journals, and acts as a library and local resource at LBL.

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88-Inch Cyclotron Operations

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The operation of the 88-Inch Cyclotron improved dramatically during the last year as the new ECR ion source came into full operation. The performance improved in several ways. New beams of higher energy became available, such as 400 MeV Ar^{11+} , 429 MeV O^{7+} and even 1 GeV $^{36}\text{Ar}^{18+}$. The beams from the cyclotron are now much more stable and frequent interruptions for PIG source changes have been eliminated. It is now possible to run the cyclotron with one operator per shift instead of two per shift required by PIG source operation.

As a national accelerator laboratory the 88-Inch Cyclotron is used extensively by outside groups from many institutions in the U.S. and abroad. Table I shows the number of users from LBL and elsewhere. Scheduling of experiments for the cyclotron has been done in an open meeting on a weekly basis with a lead time of eight days. Outside users who must make travel arrangements in advance are accommodated with advance scheduling. The members of the Users' Executive Committee for the period covered by this report were Karl van Bibber (Stanford University), Chairman; Frank S. Dietrich (Lawrence Livermore National Laboratory); and Marie-Agnes Deleplanque (LBL). The Program Advisory Committee consisted of C. Konrad Gelbke (Michigan State University), Chairman; Charles Goodman (Indiana University); and Jørgen Randrup (LBL).

The 88-Inch Cyclotron plays a significant educational role. In FY85 ten graduate students from the University of California at Berkeley employed this facility in their research toward the Ph.D. degree. Eleven graduate students from other universities participated in research at the cyclotron.

The cyclotron operated 14-1/2 eight hour shifts per week with one additional shift for maintenance at the beginning of the week and one half shift for shutdown for the weekend. The distribution of cyclotron time is shown in Table II. The available heavy ion beams are shown in Fig. 1. The light ion beams of protons, deuterons, ^3He and α -particles are available using either the ECR source or the standard internal filament source. The polarized ion source still provides beams of polarized protons and deuterons. Heavy ions ($A > 4$) occupied 71% of the scheduled time.

The main improvement was the first operation of the ECR source for experiments. This is described in a separate article in this report.

The electrical and electronic improvements included the installation of a 1 kW solid state RF amplifier to replace the tube type distributed amplifier for driving the final amplifier of the cyclotron RF system. This will increase operating reliability. A new 2 MVA transformer was installed on the pad and connected to the 12 kV line. Its 480 V power distribution switch gear system was also installed. The cyclotron main magnet will be connected to this transformer to avoid periodic power overloads on the old transformer. Other new load items can then be connected to the old transformer, as required.

In the experimental areas, a new chamber and experimental station was installed in the Cave 4 beamline. It is now in use. Two new turbomolecular

pumps have been purchased, and one has been installed on a beamline in Cave O, giving an important improvement in the vacuum in that line.

For the building, two flammable gas venting stacks were fabricated and installed. These will allow two groups to use flammable gases at the same time.

Table I		
Number of Cyclotron Users in FY85		
LBL Staff, U.C. Berkeley		22
Graduate Students		21
U.C. Berkeley	10	
Other Universities	11	
Post-doctoral Scientists		14
LBL	6	
Other Laboratories	8	
Outside Visitors and Users		120
Industry	88	
National Labs	32	
Universities		
		<u>177</u>

Table II		
Cyclotron Time Distribution for FY85		
Operating Time	Hours	%
Machine Studies	412	6.6
Axial Injection Tests	128	2.0
Cyclotron Tuning	392	6.2
ECR Tuning	94	1.5
Optics	309	5.0
On Target	4017	64.0
Waiting for Experimenter	32	0.5
	5384	85.8
Maintenance Time		
Scheduled Maintenance	644	10.2
Ion Source Changes	32	0.5
Unscheduled Maintenance	146	2.3
Other (power outages)	79	1.2
	901	14.2
	6285	100.0
Holiday/Shutdown	2475	
Total Time	8760

Fig. 1. Beams available from Cyclotron. These external beams are in electrical μ A on the first beam stop with a 2 inch X collimator gap. Natural isotopic source feeds were used.

XBL 8511-11938

Special Sabbatical Task Force in Nuclear Theory

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With the lucky coincidence of sabbatical leaves at LBL by three professors in nuclear theory, a temporary theory task force was created. The VAX networks at the Bevalac, primarily JANUS and BEVAX, offered these visitors substantially greater computing power than their home laboratories could provide. In various combinations, the team addressed nuclear theoretical problems, primarily in low-energy nuclear structure of deformed rare earth nuclei including high spin and non-zero temperature regimes. Some work on peripheral processes at Bevalac energies and at barrier energies was also done.

PART II: EXPERIMENTS

Observation of the First $T_Z = -5/2$ Nuclide, ^{35}Ca , via its β -Delayed Two-Proton Emission*

J. Äystö,[†] D.M. Moltz, X.J. Xu,[‡] J.E. Reiff, and Joseph Cerny

As experiment defines the proton drip line in the light nuclei, current interest centers on investigating those nuclides with $T_Z = (N-Z)/2 = -5/2$ which are predicted to beta decay but which have not yet been observed. Four exotic light nuclei with $Z \leq 20$ and $T_Z = -5/2$ are predicted by the updated Kelson-Garvey charge symmetry approach^{1,2} to be bound to ground state proton emission: ^{23}Si , ^{27}S , ^{31}Ar ,³ and ^{35}Ca . We wish to report the observation of ^{35}Ca detected via its beta-delayed two-proton emission.

^{35}Ca nuclei were produced by bombarding a 2 mg/cm² natural calcium target with 135 MeV ^3He beams of 3–7 μA intensity from the 88-Inch Cyclotron. Recoiling product nuclei were thermalized in 1.4 atm helium and transported through a 60 cm long and 1.27 mm diameter capillary via NaCl aerosols onto a rotating catcher wheel in the counting chamber. This experimental setup is described in ref. 4. The detector system consisted of two three-element telescopes: a 10 or 16 μm $\Delta E1$, a 250 μm $\Delta E2$, and a 500 μm E.

The two-proton coincidence spectrum collected during the bombardment of a Ca target for 2.1 C is shown in Fig. 1. Two sum peaks are evident with laboratory energies of 4089 ± 30 keV and 3287 ± 30 keV. A half-life of 50 ± 30 ms was estimated for both groups by comparison with isotopes of known half-lives at different catcher wheel speeds. The assignment of the observed groups to ^{35}Ca is based on excellent agreement with the predicted decay energy for the higher sum peak populating the ^{33}Cl ground state^{1,5} and with the known energy difference for the decays to the ground (G) and the first excited (X) states at 811 keV in ^{33}Cl . Corroborating arguments for this assignment include agreement with various reaction energetics and the expected absence or non-existence of nearby $T_Z = -2$ and $-5/2$ nuclides with similar predicted decay modes.

Fig. 1. Beta-delayed two-proton sum spectrum of ^{35}Ca . Groups labeled by G and X are related to the two-proton transitions to the ground and first excited states in the daughter nucleus, ^{33}Cl . Part of the continuum in the spectrum below 3 MeV is due to positron scattering between the detector wafers.

XBL 859-3777

Fig. 2 presents the superimposed individual proton spectra corresponding to the decays to the ground state and the first excited state at 811 keV of ^{33}Cl . The distribution of individual proton energies clearly suggests a sequential decay process via intermediate states in ^{34}Ar .

The proposed partial decay scheme for ^{35}Ca is shown in Fig. 3. The branching of the superallowed β^+ decay to the isobaric analog state ($T=5/2$) is calculated by assuming a Fermi decay with $\log ft=3.09$. The ground state spin for ^{35}Ca is taken from its mirror nucleus ^{35}P . Only the isospin forbidden two-proton decay via the intermediate state in ^{34}Ar is shown.

The present study has demonstrated that specific detection of beta-delayed two-proton decay can also be an effective tool in searches for new and exotic nuclides near the proton drip line.

Fig. 2. Individual proton energy spectrum from the beta-delayed two-proton spectrum of ^{35}Ca to the ground state (a) and first excited state (b) of ^{33}Cl .

XBL 855-8887

Footnotes and References

* Condensed from Phys. Rev. Lett. **55**, 1384 (1985).

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Fig. 3. Proposed partial decay scheme for the beta-delayed two-proton emission of ^{35}Cl . XBL 855-8889

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Trends in the Study of Light Proton Rich Nuclei*

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Studies of light proton rich nuclei are of particular interest for many reasons: for example, in investigating the role of charge-dependent effects in nuclear systems, for probing the limits of particle stability and in searching for new radioactive decay modes. In recent years a number of new beta-

delayed proton emitters have been discovered, including the $T_z = -3/2$ nuclei ^{27}P and ^{31}Cl , and the $T_z = -2$ nuclei ^{22}Al , ^{26}P and ^{36}Ca . The masses of ^{24}Si , ^{28}S , ^{32}Ar and ^{40}Ti have been determined from measurements of reaction Q-values. ^{22}Al and ^{26}P were found to decay by beta-delayed two-proton em-

ission, a new mode of radioactivity predicted by Goldanskii.¹

Two proton emission following beta decay can in principle proceed via sequential emission, ^2He emission or simultaneous uncoupled emission. The observed peak structure of the individual protons from the decay of ^{22}Al and their angular distributions suggest sequential emission, although a small admixture (<15%) of ^2He emission cannot be ruled out.²

The phenomenon of beta-delayed two-proton decay is possible only for very neutron-deficient nuclei and therefore provides a sensitive technique for searching for the decays of such nuclei. This allowed the detection of the decay of ^{35}Ca (a separate contribution to the annual report) in the presence of many delayed single proton emitters, avoiding on-line mass separation which was required to study ^{36}Ca . Additional examples of beta-delayed two-proton emitters may be sought among the $A=4n+2$, $T_z=-2$ nuclei such as ^{46}Mn and ^{50}Co . However, our preliminary searches for these isotopes among the products of $^{14}\text{N} + ^{40}\text{Ca}$ reactions at 135 and 180 MeV have proven inconclusive. Certain nuclei in the sd shell, with $T_z \leq -5/2$, can be expected to decay by $\beta 2p$ emission, in particular ^{22}Si , ^{23}Si , ^{27}S and possibly ^{31}Ar .

For exotic nuclei at the proton drip line there exists the possibility that some nuclei might decay by ground state two-proton radioactivity. Among the light nuclei, mass predictions using the Kelson-Garvey formula suggest that ^{19}Mg , ^{31}Ar and ^{39}Ti remain as candidates for this new decay mode.

In view of the success of heavy-ion deep inelastic and fragmentation reactions in the production of highly neutron-rich nuclei, we are investigating the possibility of using this technique to produce proton-rich nuclei, and to probe the proton drip line. A 15.5 MeV/nucleon ^{36}Ar beam from the 88-Inch Cyclotron, injected by the ECR ion source, has been used to bombard a thick calcium target. Reaction products emitted at 5° were detected in the focal plane of the magnetic spectrometer, using a detection system that has been described previously.³ Measurements of magnetic rigidity $B\rho$, time-of-flight T and differential energy loss ΔE allowed identification of

the wide range of nuclei so produced. The combination of $B\rho$ and ΔE can be used to produce a mass spectrum, as shown in Fig. 1(a). Adequate separation of masses is achieved up to $A \sim 30$. An example of a m/q spectrum ($m/q \propto B\rho \cdot T$) for $A=30$ (Fig. 1(b)) illustrates how isobaric nuclei are separated. These data are preliminary; further experimental data and analysis at other energies will be required to establish the optimum yields of proton-rich nuclei.

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Fig. 1. a) Mass distribution for the reaction 15.5 MeV/nucleon $^{36}\text{Ar} + \text{Ca}$ and b) the corresponding m/q distribution for mass 30. XBL 8511-4605

Beta-Delayed Proton Decays of ^{27}P and ^{31}Cl : A Study of Gamow-Teller Decays with Large Q-Values*

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Intense proton emission associated with superallowed beta decay to the isobaric analog state (IAS) has offered a unique way of establishing the existence and decays of several $T_Z = -3/2$ nuclei.¹ The $A=4n+3$, $T_Z = -3/2$ series of nuclei, however, exhibit only weak beta-delayed proton emission because of proton-bound isobaric analog states. Observation of these nuclei has been hindered both by small proton branching ratios ($\approx 10^{-4}$) and by severe beta-gamma background. All of the members of this series have been discovered via their weak beta-delayed proton emission. We wish to report the discovery of the newest member of this series, ^{27}P , and additional work on another member, ^{31}Cl .

^{27}P and ^{31}Cl were produced in 45 MeV proton bombardments of Si and ZnS targets at the 88-Inch Cyclotron. Products were collected and assayed by using the helium jet transport technique in conjunction with a rotating catcher wheel placed directly in front of a detector telescope consisting of an $8.3\text{ }\mu\text{m}$ ΔE , a $68\text{ }\mu\text{m}$ E and a $200\text{ }\mu\text{m}$ E_{rej} . The same targets were irradiated with a 28 MeV proton beam in order to produce the beta delayed proton precursors ^{28}P and ^{32}Cl , which were used for energy and efficiency calibrations of the detector telescope. Varying the catcher wheel speed permitted determination of the half-lives for these activities.

Beta-delayed proton spectra obtained in proton bombardments of Si at 28 and 45 MeV are shown in Fig. 1. The lower energy bombardment produced a pure ^{28}P spectrum. Increasing the beam energy to 45 MeV resulted in the appearance of two new proton groups at 730 keV and 1235 keV, which were assigned to ^{27}P . These groups were found to decay with a half-life of 260 ± 80 ms, in agreement with previous calculations² for ^{27}P . A partial decay scheme for ^{27}P is presented in Fig. 2. Its ground state spin and parity of $1/2^+$ are based on its mirror nucleus ^{27}Mg .³

Fig. 1. Proton spectra resulting from the bombardments of Si targets with (a) 45 MeV and (b) 28 MeV protons corresponding to integrated beam currents of 330 and 110 mC, respectively. Exact intensities and energies of the labeled peaks in the ^{28}P spectrum can be found in ref. 7. The lower energy cutoff is slightly below 700 keV. This can be seen from the weak appearance of the 680 keV proton group P_2 in (b), which was the strongest proton group observed in ref. 7.

XBL 8501-6939

Spectra for ^{32}Cl and ^{31}Cl were obtained using the method outlined above. The ^{31}Cl half-life was found to be $150 \pm 25 \mu\text{s}$, in agreement with earlier observations.^{4,5} The decay scheme of ^{31}Cl is similar to that of ^{27}P , presented in Fig. 2.

Calculated $\log ft$ values for the beta decays preceding the proton emissions observed from ^{27}Si and ^{31}S indicate that these are allowed Gamow-Teller decays. The experimental results are consistent with a shell model calculation⁶ predicting clustering of Gamow-Teller strength above the IAS and also with an often observed quenching of the Gamow-Teller strength by a factor of 0.6.

Fig. 2. Proposed partial decay scheme of ^{27}P . Decays which have not been directly seen are indicated as dashed lines. XBL 851-6941A

Footnotes and References

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Shape Changes in the Light Krypton Isotopes: ^{73}Kr

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Recent experiments¹ have shown that the light neutron-deficient krypton isotopes exhibit strong prolate ground state deformation. Additional evidence from in-beam gamma-ray experiments² demonstrates spherical shape coexistence in these nuclei. Although some results have suggested changes from the prolate shapes to triaxial shapes in $Z = 37, 38$ nuclei, no evidence for prolate-to-oblate changes have been found despite theoretical calcula-

tions³ that the potential well for oblate shapes is nearly as deep as that for prolate shapes. Several theories⁴ predict, however, that the ^{73}Kr ground state should provide the first example of a strongly oblate nucleus in this mass region ($\beta_2 \sim .35$).

It was decided to investigate this problem via in-beam γ -ray spectroscopy. Unfortunately, most compound nuclear reactions in this mass region ca-

pable of producing ^{73}Kr tend to deexcite via charged particle emission. To overcome this difficulty, we employed the $^{40}\text{Ca}(^{36}\text{Ar},2\text{pn})$ reaction to observe ^{73}Kr . Neutron-gamma coincidences have also been employed to distinguish ^{73}Kr γ rays from those of ^{73}Br produced in the competing $^{40}\text{Ca}(^{36}\text{Ar},3\text{p})$ reaction. ^{36}Ar beams from the 88-Inch Cyclotron with $E_b = 90\text{--}105$ MeV impinged on a $250\text{ }\mu\text{g}/\text{cm}^2$ ^{40}Ca target deposited on a thick tantalum substrate and covered with ~ 50 Å of Au to reduce the oxidation rate. Fig. 1 shows the relative excitation functions for $^{49}\text{Cr}(^{16}\text{O}(^{36}\text{Ar},2\text{pn})^{49}\text{Cr})$, ^{73}Kr and ^{73}Br . This excitation function permitted us to choose the proper bombardment energy (100 MeV) to maximize the ^{73}Kr production while minimizing the ^{73}Br production.

Our ^{73}Kr search was aided by recent results⁵ on ^{73}Br which have been verified in our experiments. Fig. 2 shows the coincidence spectrum for the most intense γ ray attributed to ^{73}Kr . This 136 keV γ ray is also in strong coincidence with prompt neutrons. Work is in progress to construct a decay scheme from the coincidence data. Comparisons with theoretical predictions should permit us to elicit the ground state shape of ^{73}Kr and thus extend our knowledge about shape changes in the light krypton mass region.

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Fig. 1. Excitation functions for selected products from the $^{40}\text{Ca}(^{36}\text{Ar},\text{xnyp})$ and $^{16}\text{O}(^{36}\text{Ar},\text{xnyp})$ reactions. Cross sections have not been normalized and therefore are only relative. XBL 8512-9587

Fig. 2. Gamma rays coincident with the 136-keV transition attributed to ^{73}Kr . XBL 8512-9588

Structure in Beta-Delayed Proton Spectra of $N = 81$ Precursors

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The recently reported^{1,2} delayed-proton spectra of ^{147}Dy and ^{149}Er show pronounced peak structure unlike other rare-earth delayed-proton precursors. The ^{147}Dy spectrum, with a high-energy cutoff of ≈ 4.5 MeV, was dominated by distinct peaks below 4 MeV. The investigation of this structure was extended to the next, previously unknown $N=81$ isotone, ^{151}Yb .

^{151}Yb was produced in the $^{96}\text{Ru}(^{58}\text{Ni}, 2\text{pn})$ reaction by bombarding a 1.5 mg/cm^2 thick target of ruthenium, enriched in ^{96}Ru to 96.5%, deposited onto a 2.0 mg/cm^2 thick HAVAR foil at the SuperHILAC. Reaction products were mass separated with the OASIS on-line separator,³ collected with a tape system and transported to a Si particle telescope consisting of a $9.1 \mu\text{m}$ ΔE and a $702 \mu\text{m}$ E detector for measuring protons. A planar HPGe detector was placed directly behind the telescope to detect x rays. Two n-type Ge detectors were used to obtain coincidence γ ray information; one of them, a 24% relative efficiency detector, faced the telescope, while the other, a 52% relative efficiency detector, was set to one side about 4.5 cm from the radioactive source. A 1 mm thick plastic scintillator was placed in front of the 24% detector so that positrons could be registered.

Fig. 1(a) shows the delayed-proton spectrum accumulated during a 48 hour period; typical beam currents were about 9×10^{11} particles per second. The half-life of the protons was measured to be 1.6 ± 0.1 s. On the basis of a new half-life in the isobaric chain, coincidences with Tm K x rays, and coincidences with several ^{150}Er γ rays reported from in-beam experiments⁴ we conclude that the protons follow the β^+ decay of the new isotope ^{151}Yb . From systematics for even Z , $N = 81$ isotones an $h_{11/2^-}$ isomer located ≈ 0.75 MeV above the $s_{1/2^-}$ ground state is expected in ^{151}Yb . Direct evidence for the $h_{11/2^-}$ isomer via Yb K x rays or the $M4 \rightarrow M1$, $h_{11/2^-} \rightarrow d_{3/2^-} \rightarrow s_{1/2^-}$ cascade was not observed. This is consistent with the estimated IT branch of

$\approx 6 \times 10^{-4}$ based on systematics of Weisskopf enhancements.⁵ The delayed-proton data, however, point to the existence of β decaying high spin and low-spin states in ^{151}Yb . Coincidences with γ rays determine that $\approx 45\%$ of the delayed protons populate the first 2^+ , 3^- , 5^- , 4^+ , and 6^+ states in ^{150}Er with the other $\approx 55\%$ decaying to the 0^+ ground state. Statistical model calculations predict 94% excited state feeding for an $h_{11/2^-}$ precursor and 96% ground state feeding for an $s_{1/2^-}$ precursor. Table I lists the experimental feedings and the statistical model predictions. The low spin and high spin states in ^{151}Yb are tentatively assigned to the $s_{1/2^-}$ and $h_{11/2^-}$ levels respectively.

The delayed-proton spectrum of ^{151}Yb , Fig 1(a), consists of discrete peaks superimposed on a statistical spectrum. Fig. 1(b) shows protons in coincidence with positrons. A strong enhancement of the peaks relative to the statistical protons is evident. Conversely, the delayed protons coincident with K α x rays, Fig 1(d), produced in electron capture decay to ^{151}Tm have a statistical distribution with little indication of structure. Fig. 1(c) is a spectrum generated by subtracting a normalized spectrum similar to Fig. 1(b) from the spectrum shown in Fig. 1(a), where the normalization was done through the lowest energy proton peak at 3.4 MeV. The 207 keV 3^- to 2^+ transition in ^{150}Er is a moderately sensitive measure of excited state feeding by the delayed protons. The protons above the highest energy peak (≈ 4.5 MeV) were in coincidence with the 207 keV transition while no positron coincident protons were observed in coincidence with the 207 keV line. This indicates that the "peak protons" populate the ground state of ^{150}Er and the statistical protons populate excited states in ^{150}Er . A calculation of the $\beta^+/\text{E.C.}$ ratio for decay to the average proton peak energy versus decay to the average statistical proton energy indicates a factor of 10 greater positron feeding to the peak region in agreement with Fig. 1(b). Since delayed protons from the $s_{1/2^-}$ state in ^{151}Yb

would predominately populate the 0^+ ground state in ^{150}Er and delayed protons from the $h_{11/2}$ state would tend to populate excited states in ^{150}Er , we conclude that the peaks are associated with the delayed-proton decay of the $s_{1/2}^+$ ground state of ^{151}Yb and the statistical delayed protons are from the $h_{11/2}^-$ isomer. These conclusions are summarized in Fig. 2.

Fig. 1. Beta-delayed proton spectra from ^{151}Yb . See text for details.

XBL 858-11674

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Fig. 2. Diagram representing the decay of ^{151}Yb . The overlaid spectra, from left to right, (1) the delayed protons observed in coincidence with the 3^- to 2^+ transition and hence associated with the $h_{11/2}^-$ precursor, (2) the delayed protons observed in coincidence with positrons implying ^{150}Er ground state feeding and hence associated with the $s_{1/2}^+$ precursor, and (3) the results of a RPA beta strength function calculation for the $s_{1/2}^+$ precursor. All energies represent excitation energy in ^{151}Tm . A proton separation energy of 400 keV for ^{151}Tm is assumed.

XBL 858-11673

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Table I. Levels in ^{150}Er populated by protons.

Energy (MeV)	Level J^π	Observed Feeding (%)	Calculated Feeding		
			Total ^{a)} (%)	$h_{11/2^-}$ ^{b)}	$s_{1/2^-}$ ^{b)}
0.000	0^+	51.3	49.5	5.1	95.8
1.579	2^+	13.7	6.2	9.8	2.5
1.786	3^-	9.9	8.2	14.4	1.7
2.261	5^-	8.6	9.0	17.6	
2.295 ^{c)}	4^+	11.5	12.8	25.1	
2.621	6^+	5.0	9.7	19.1	
2.633	7^-	2.5	4.9		
2.734	8^+	2.0	4.0		

a) Calculated feeding for an assumed 50–50 mixture of $h_{11/2^-}$ and $s_{1/2^-}$ precursors.

b) Calculated relative feeding normalized to 100.

c) Level observed for the first time in this study.

Recent Experimental Results from OASIS

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Our on-going study^{1–4} of the decay properties of very neutron-deficient lanthanides has resulted in the identification of several new isotopes and new beta-delayed proton branches. Some results are presented below by mass number.

A=127 A delayed proton activity with a half-life of 1.5 ± 0.3 s was assigned to ^{127}Nd on the basis of the Pr K x rays observed in coincidence with the protons. This confirms the previous Z assignment of this precursor.² A gamma ray of 169.9 keV was observed in coincidence with the delayed protons and is tentatively assigned to the 2^+ to 0^+ transition in ^{126}Ce .

A=128 In a previous experiment a delayed proton activity was observed at this mass number with a half-life of 4 ± 2 s.² This activity was incorrectly assigned to ^{128}Nd on the basis of cross-section and half-life predictions. The weak beta-delayed proton activity with a half-life of $3.2 \pm 0.5 - 0.4$ s observed in coincidence with Ce K x rays can now be unambiguously assigned to the new isotope ^{128}Pr [4]. No evidence for beta-delayed proton decay from ^{128}Nd was observed. ^{128}Pr was

also identified by its beta decay to the known rotational levels in ^{128}Ce . The decay analysis of the gamma rays from the de-excitation of the 2^+ and 4^+ levels in ^{128}Ce yields a half-life of 3.0 ± 0.1 s in good agreement with the proton half-life, but considerably shorter than the value of 9 s predicted by the gross theory of beta decay.⁵

A=131 A delayed proton activity with a half-life of 1.4 ± 0.2 s was assigned to the new isotope ^{131}Sm on the basis of Pm K x rays observed in coincidence with the protons. A second delayed-proton activity with a half-life of 25 ± 4 s was assigned to ^{131}Nd ⁶ on the basis of half-life and Pr K x rays observed in coincidence with the protons. Strong gamma rays of 158.9 and 254.0 keV observed in coincidence with protons can be assigned to the 2^+ to 0^+ transitions in ^{130}Nd and ^{130}Ce respectively. This is the first measurement of the energy of the 2^+ level in ^{130}Nd and agrees well with the systematics for Nd isotopes.⁴

A=133 A beta-delayed proton activity with a half-life of 3.2 ± 0.4 s was assigned to ^{133}Sm by Bog-

danov *et al.*⁶ based on systematics for delayed proton emission. We observed a strong delayed proton activity in coincidence with Pm K x rays confirming this activity as ¹³³Sm. Our half-life value of 2.8 ± 0.2 s is in reasonable agreement with the above result. A strong feeding of the lowest 2+ level in ¹³²Nd was observed in coincidence with the protons. This is the first observation of the 2+ level in ¹³²Nd. Its energy of 213.0 keV agrees well with the value expected from the systematics for this region.⁴

A=144 A short lived proton emitter with a half-life of 0.7 ± 0.1 s was assigned to the new isotope ¹⁴⁴Ho on the basis of Dy K x rays observed in coincidence with the protons. A second delayed proton activity with a half-life of 7 ± 3 s can be tentatively assigned to the new isotope ¹⁴⁴Dy on the basis of Tb K x rays observed in coincidence with the protons. This is the heaviest known case of the rare even-N precursors. The beta decay of ¹⁴⁴Dy was observed directly and the half-life of 9.1 ± 0.05 s from the decay of the strongest gamma rays is in agreement with the half-life for the protons. No strong evidence for the expected delayed proton decay of ^{144m}Tb was observed.

A=146 Beta-delayed protons with a half-life of 3.1 ± 0.6 s observed in coincidence with Dy K x rays can be assigned to ¹⁴⁶Ho. This is the first observation of the delayed proton branch in ¹⁴⁶Ho.

A=149 A 9.4 ± 1.0 s delayed proton activity in

coincidence with Ho K x rays was observed and can be assigned to ¹⁴⁹Er. The delayed proton spectrum consists of peaks superimposed on a "statistical" background confirming the work in ref. 7.

A=152 Beta-delayed protons with a half-life of 0.60 ± 0.08 s, observed in coincidence with Yb K x rays, can be assigned to ¹⁵²Lu. This is the heaviest odd-odd precursor identified to date.

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Decay Studies of ¹⁴⁶Ho, ¹⁴⁶Dy, and ¹⁴⁶Tb with Mass-Separated Sources

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Radioactive properties of A=146 nuclides were investigated with the use of the OASIS on-line isotope separator following their production in ⁵⁸Ni bombardments of ⁹²Mo. Three isotopes were ob-

served in our 12 s irradiation and counting cycles, i.e., ¹⁴⁶Ho (3.6 s), ¹⁴⁶Dy (29 s), and the low-spin isomer of ¹⁴⁶Tb (~8 s) which was not produced directly in the ⁵⁸Ni bombardments but grew in from the de-

cay of ^{146}Dy .

The β decay of ^{146}Ho has been studied previously.¹ Our data generally confirm the earlier γ -ray energies and intensities as well as the proposed¹ decay scheme (Fig. 1). We also observed delayed protons, for the first time, following the β^+ decay of ^{146}Ho . The nuclidic assignment for these protons was based on coincidences with Dy K x rays and on half-life measurements. Our γ -ray intensities remove a severe imbalance at the 683 keV 2^+ ^{146}Dy level which had prompted the previous investigators¹ to suggest the existence of a low-spin isomer in ^{146}Ho . We saw no evidence either for Ho K x rays or for the presence of another half-life in ^{146}Ho decay.

At least 30 γ rays were found to be associated with ^{146}Dy decay in contrast to the results reported in ref. 2, where only two transitions were assigned to this nuclide. Construction of the decay scheme is still in progress; at this time four excited levels can be placed in ^{146}Tb (Fig. 1). In agreement with Nolte *et al.*² we assign a J^π of 1^+ to the ^{146}Tb low-spin isomer since 90% of its decay strength proceeds directly to the ^{146}Gd ground state with the remaining 10% distributed evenly between the first 2^+ and 0^+ excited states (Fig. 1).

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Fig. 1. Proposed partial decay schemes for ^{146}Ho , ^{146}Dy , and ^{146}Tb .
XBL 8511-9586

Gamow-Teller β -Strength of the New Isotope ^{151}Yb

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In another contribution to this report the discovery of the ground state and isomeric state of the new isotope ^{151}Yb is discussed. The beta-delayed proton decay of ^{151}Yb covers a range of excitation energies from 3 to 9 MeV in the intermediate magic nucleus ^{151}Tm . In general it is difficult to obtain detailed spectroscopic information at such high excitation energies and we have therefore explored the pos-

sibilities of extracting more global information—reflected for example in the beta strength function—from a combination of experimental and theoretical studies of beta-delayed proton decay.

Beta-delayed proton decay is a two-step process: beta decay to high excitation energies in the intermediate nucleus (≥ 3 MeV for lanthanides) fol-

lowed by proton decay. The beta-decay intensity at high level densities can be described in the usual form¹

$$\langle I_{\beta}^i \rangle_{E_p} = \langle f \cdot S_{\beta}^i(E_{\beta}) \rangle \quad (1)$$

and average intensity of protons with energy E_p is given by

$$I_p(E_p) = \sum_{i,f} \langle I_{\beta}^i \rangle_{E_p} \left\langle \frac{\Gamma_p^{if}}{\Gamma_p^i + \Gamma_{\gamma}^i} \right\rangle_{E_p} \quad (2)$$

where indices i and f denote intermediate and final states respectively. Γ_p is the proton and Γ_{γ} the gamma width. $\langle \rangle$ symbolizes the (Porter-Thomas) statistical mean. In eq. (1) f is the statistical rate function and S_{β} the β -strength function. Equation (2) is simplified when the proton decay occurs for *one* well defined final state in the daughter nucleus. Equations (1) and (2) can then be combined to yield an expression for the β -strength function of the precursor nucleus

$$S_{\beta}(E_x) = \frac{I_p(E_x)}{f \cdot \left(\frac{\Gamma_p(E_x)}{\Gamma_p(E_x) + \Gamma_{\gamma}(E_x)} \right)} \quad (3)$$

where all variables have been expressed as functions of the excitation energy E_x in the intermediate nucleus. The right side of eq. (3) represents an experimental spectrum $I_p(E_x)$ divided by a "theoretical proton spectrum" (with $S_{\beta} = \text{const.}$) that can be calculated—in the case of high level densities—from a statistical model.² We have carried out such calculations for the ground-state (g.s.) and the isomeric state of ^{151}Yb . Fig. 1b shows the "theoretical proton spectrum" for the decay of $^{151}\text{Yb}(1/2^+)_{\text{g.s.}}$ to $^{150}\text{Er}(0^+)_{\text{g.s.}}$; Fig. 1a represents the sum of the statistical rate functions for electron capture and β -decay, and Fig. 1c is the ratio of the proton width to the total decay width. Next, the experimental proton spectrum shown in Fig. 1b of a previous contribution (Structure in Beta-Delayed Proton Spectra of $N=81$ Precursors) was divided according to eq. (3) by the "theoretical spectrum" (Fig. 1b of this article) and the result is shown as the histogram in Fig. 2;³ it represents the experimental β -strength function of $^{151}\text{Yb}(g.s.)$.

Fig. 1. Statistical model calculations for $^{151}\text{Yb}(1/2^+)_{\text{g.s.}} \rightarrow ^{150}\text{Er}(0^+)_{\text{g.s.}}$; $Q_{\text{EC}}(^{151}\text{Yb}) = 10$ MeV, proton separation energy for ^{151}Tm $S_p = 39$ MeV: a) Sum of the statistical rate functions for electron capture and β^+ decay, b) product of the statistical rate functions and $\Gamma_p/\Gamma_{\text{total}}$, and c) $\Gamma_p/(\Gamma_p + \Gamma_{\gamma})$.
XBL 8510-4357

Fig. 2. Gamow-Teller β -strength functions for $^{151}\text{Yb}(1/2^+)_{\text{g.s.}}$. Experimental β -strength function derived from the beta-delayed proton spectrum (histogram), large-basis shell model calculation (see text) (a), random phase approximation calculations with $\epsilon_2 = -.150$ (b), and $\epsilon_2 = -.098$ (c).
XBL 8510-4358

Fig. 2 also shows the results of three Gamow-Teller β -strength calculations: Fig. 2a is a large-basis shell model calculation using the Lanczos algorithm and a realistic finite-range two body interaction of Kallio and Kollveit,⁴ while in Figs. 2b and 2c a random phase approximation code was used.⁵ The ¹⁵¹Yb g.s. deformation in Fig. 2c is $\epsilon_2 = -.098$ which represents the mass/energy minimum in the $\epsilon_2 - \epsilon_4$ plane for this nucleus. In Fig. 2(b) the deformation was arbitrarily increased to $\epsilon_2 = -.150$. A comparison between the experimental and the calculated β -strength function shows that only the shell-model Lanczos-method has a sufficiently large basis to reproduce the experimental result correctly. This is, however, obtained at a considerable price: several hours of CPU-time on a CRAY X-MP for Fig. 2a versus a few minutes on a VAX 8600 for Figs. 2b and 2c.

It was already pointed out that eq. (3) is only valid for decays to *one* well defined state. In the case of beta decay from the *isomeric* state of ¹⁵¹Yb the protons decay to *several* excited states in the daughter nucleus giving rise to the proton spectrum shown in Fig. 1(c) of the previous contribution. In this case, statistical model calculations for the lowest eight levels in ¹⁵⁰Er were carried out and the resultant "theoretical proton spectrum" was used to obtain the experimental β -strength function for ^{151m}Yb(11/2⁻) shown in Fig. 3.³ The smooth curve in Fig. 3 represents the result of the large-basis shell model calculation for ^{151m}Yb which is again in good agreement with the experiment.⁶

The authors wish to thank P. Möller for making his β -strength code available to us, and K. Takahashi and G. Mathews for carrying out the shell-model Lanczos calculations on the CRAY X-MP.

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Fig. 3. Gamow-Teller β -strength functions for ^{151m}Yb(11/2⁻). Experimental β -strength function derived from the β -delayed proton spectrum (histogram) and large-basis shell model calculation (smooth curve). XBL 8510-4359

The s-Process Branch at ^{148}Pm

E.B. Norman, K.T. Lesko, R.M. Larimer, and S.G. Crane

Recent neutron capture cross section measurements on $^{148,150}\text{Sm}$ have shown that ^{148}Pm is a branch point in the path of the s- (slow) neutron capture process.¹ As is the case at a number of other places along this path, the half-life of ^{148}Pm is sufficiently long that neutron captures on this radioactive nucleus can begin to compete with the normal beta decays. The relative rates for these two processes depend sensitively on the s-process neutron flux, and thus such branches provide a means to infer the neutron density at which the s-process occurs.

The situation at ^{148}Pm is complicated by the fact that the ground state has $J^\pi = 1^-$ and a half-life of 5.4 days, while 137 keV above this there is a $J^\pi = 6^-$ isomer with a half-life of 41.3 days. In addition to having quite different half-lives, calculations indicate that $^{148}\text{Pm}^{g,m}$ will have very different neutron capture cross sections. Thus Käppeler² has shown that the inferred s-process neutron density derived from the ^{148}Pm branch depends sensitively on whether or not $^{148}\text{Pm}^{g,m}$ are in thermal equilibrium

at the temperatures and densities found in the helium-burning zones of red-giant stars.

To decide this issue, the positions and decay modes of ^{148}Pm excited states must be known. In order to provide this information, we have performed in-beam γ -ray singles and γ - γ -t coincidence experiments using Ge detectors. ^{148}Pm was produced by the $^{148}\text{Nd}(p,n)$ reaction at bombarding energies of 7–8 MeV. A number of γ -ray lines were observed between 75 and 500 keV. Coincidence relations have been established for many of these γ -rays. A level scheme of ^{148}Pm incorporating these results is now being constructed. With this information it should then be possible to decide whether or not $^{148}\text{Pm}^{g,m}$ are in thermal equilibrium during the s-process and hence the neutron density inferred from this branch point.

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Nucleosynthesis of ^{180}Ta

S.E. Kellogg, R.M. Larimer, K.T. Lesko, D.M. Moltz, and E.B. Norman*

We have continued our studies, begun at the University of Washington, of the possible s- and r-process contributions to the production of ^{180}Ta . We performed an experiment this year at the University of Washington to search for the beta decay of $^{180}\text{Hf}^m$ to $^{180}\text{Ta}^m$. A source of $^{180}\text{Hf}^m$ was mounted in close geometry to a silicon surface-barrier detector, and this assembly was then positioned inside a nearly 4π NaI anti-coincidence shield. The intense conversion electrons emitted in the electromagnetic decay of $^{180}\text{Hf}^m$ were distinguished from betas by the fact that the conversion electrons are each accompanied by 2–3 γ -rays while the betas will have nothing in coincidence with them. The NaI shield provided very high veto efficiency and as a result we should be sensitive to a beta decay branch as small as 0.5%. Data from this experiment are currently being analyzed.

We have also performed an experiment at LBL to search for a possible high-spin isomer in ^{180}Lu that beta decays to $^{180}\text{Hf}^m$. ^{180}Lu was produced by the $^{180}\text{Hf}(n,p)$ reaction using fast neutrons produced via the $^9\text{Be}(d,n)$ reaction. In our first experiment, we searched for γ -rays from activities with half-lives greater than about 1 minute. In order to provide sensitivity to much shorter-lived species, a pneumatic target transfer system (rabbit) is now being installed in Cave O at the 88-Inch Cyclotron, and a new search using this system is planned for the near future.

Footnotes and References

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Improved Limits on the Double Beta Decay Half-Lives of ^{50}Cr , ^{64}Zn , ^{92}Mo , and ^{96}Ru *

E.B. Norman

While there has been much experimental effort devoted to searches for double β^- decay, comparatively little work has been done on double β^+ , β^+ /electron-capture and double electron-capture decay. To date, there are no conclusive laboratory observations of any double beta decay mode. However, because of the possible implications for lepton-number conservation and for the mass of the neutrino it is important to search for evidence of these processes with the greatest sensitivity currently possible. In the present work, searches have been made for the β^+ /EC decays of ^{50}Cr , ^{64}Zn , ^{92}Mo , and ^{96}Ru , and for the $\beta^+\beta^+$ decay of ^{96}Ru . The possible decay schemes of these nuclei are shown in Fig. 1. For each of these nuclei, a ground state $\rightarrow$ ground state β^+ /EC decay is possible. For ^{96}Ru , β^+ /EC decays to excited states below 1.698-MeV excitation energy in ^{96}Mo are also energetically allowed, as is a ground state $\rightarrow$ ground state $\beta^+\beta^+$ decay.

If a β^+ /EC or a $\beta^+\beta^+$ decay occurred within a thick sample of material, almost all of the positrons would stop and annihilate within the sample. Subsequently, either two or four strongly correlated coincident 511-keV annihilation gamma rays would be emitted. To detect the gamma-ray signatures of β^+ /EC or $\beta^+\beta^+$ decay, two 110-cm³ high-purity Ge detectors were used. The sample under study was sandwiched directly between the front faces of the two detectors. This assembly was shielded by approximately 10 cm of lead on all sides. An event of possible interest was defined to be one for which there were coincident signals in the two detectors, and in which 511 keV was deposited in one of them. For such events the energy signals of the two detectors were summed together. A signature of ground state $\rightarrow$ ground state β^+ /EC decay would thus be a summed-energy line at 1022 keV, and the signal from β^+ /EC decay to a state at an excitation energy E_x in the daughter nucleus would be a line at $(1022 + E_x)$ keV.

Fig. 1. Possible decay schemes of (a) ^{50}Cr , (b) ^{64}Zn , (c) ^{92}Mo , and (d) ^{96}Ru . Q_{KK} is the ground state $\rightarrow$ ground state double electron-capture decay energy.

XBL 8412-5333

The Cr, Zn, Mo, and Ru samples were counted for totals of 163, 161, 147, and 178 h, respectively. Al and Cu blanks were similarly counted for 138 and 108 h, respectively. Spectra obtained from the Zn sample and from the Al blank are shown in Fig. 2. The spectra observed from all samples were very similar in overall shape and in the total number of counts obtained per unit time. In all spectra the only well-defined peaks are those at 1022 and 1461 keV. The 1461-keV line arises from the decay of the well-known long-lived isotope ^{40}K , which is present in the building materials. The 1022-keV line appears to be the result of high-energy γ -rays pair producing within the sample under study.

Fig. 2. Summed energy gamma-ray spectra observed in (a) 72.7 h of counting the Zn sample, and (b) 69.3 h of counting the Al "blank." XBL 8412-6011

The counting rates in the 1022-keV peak observed from the Cr, Zn, Mo, and Ru samples were (within the statistical uncertainties) equal to those seen from the Al and Cu blanks. The net 1022-keV counting rate possibly attributable to β^+ /EC decay was obtained by subtracting the average rate ob-

served from the Al and Cu blanks from the rate observed with each sample. These net rates, together with the resulting 1σ uncertainties, were then used to set upper limits on the net numbers of counts in each peak. From this analysis, 68% confidence level lower limits have been established on the half-lives of ^{50}Cr , ^{64}Zn , ^{92}Mo , and ^{96}Ru against ground state $\rightarrow$ ground state β^+ /EC decay. Searches were also made for ^{96}Ru β^+ /EC decays to excited states in ^{96}Mo . No evidence of a peak was found at any of the expected positions. The results of these investigations are summarized in Table I. The limits established in the present study represent improvements of factors of 500-1200 over those obtained in previous similar investigations. However, they are still well below the most recent theoretical estimates of the half-lives for these double beta decay processes.

Footnotes and References

* Condensed from Phys. Rev. C 31, 1937 (1985).

Table I
Lower Limits on the Half-Lives of ^{50}Cr , ^{64}Zn , ^{92}Mo , and ^{96}Ru Established in the Present Study

Decay	Mode	Final state $J^\pi, E_x(\text{keV})$	$t_{1/2}$ (years)
$^{50}\text{Cr} \rightarrow ^{50}\text{Ti}$	β^+ /EC	$0^+, 0$	1.8×10^{17}
$^{64}\text{Zn} \rightarrow ^{64}\text{Ni}$	β^+ /EC	$0^+, 0$	2.3×10^{18}
$^{92}\text{Mo} \rightarrow ^{92}\text{Zr}$	β^+ /EC	$0^+, 0$	3.0×10^{17}
$^{96}\text{Ru} \rightarrow ^{96}\text{Mo}$	β^+ /EC	$0^+, 0$	6.7×10^{16}
"	"	$2^+, 778$	6.0×10^{16}
"	"	$0^+, 1148$	4.5×10^{16}
"	"	$2^+, 1498$	5.5×10^{16}
"	"	$2^+, 1626$	5.3×10^{16}
"	"	$4^+, 1628$	5.3×10^{16}
"	$\beta^+\beta^+$	$0^+, 0$	3.1×10^{16}

Improved Tests of the Exponential Decay Law

E.B. Norman, S.B. Gazes, and S.G. Crane

Over the years, numerous authors have pointed out that the exponential nature of the radioactive decay law is only an approximation.¹⁻⁴ Deviations from purely exponential behavior may in fact be expected at very short and/or very long times compared to the lifetime of the decaying system. While there is general agreement that such deviations should occur, the time interval over which they have their maximum size, and even the functional form that they take, are still open questions.

We have reexamined the β -decays of ^{198}Au ($t_{1/2}=2.696$ days) and ^{56}Mn ($t_{1/2}=2.5785$ hours) to test the exponential nature of the decay law at short and long times, respectively. Sources of ^{198}Au and ^{56}Mn were prepared by neutron irradiation at the U.C. Berkeley TRIGA reactor and were transported to the 88-Inch Cyclotron building for γ -ray counting.

A 10 μCi ^{198}Au source was produced in a 12 millisecond (FWHM) neutron pulse at the reactor. Counting was begun within 0.002 half-lives, and the decay rate from this "new" sample was compared to that of a previously prepared "old" ^{198}Au sample, i.e. a source that was about 1 half-life old. Simultaneous measurements of these two sources eliminate (or at least reduce) many potential sources of systematic errors. Data were accumulated in 0.01-, 0.1-, and 1-second-long time bins over a period of three days. These measurements showed that the ratios of the decay rates from the "new" and "old" ^{198}Au samples were constant over all time intervals studied – as would be expected for purely exponential decay.

Sources of ^{56}Mn ranging in initial activity from 1 microCurie to 1000 Curies were produced by irradiating very high purity Mn metal chips. Following activation, each source was allowed to "cool" until the ^{56}Mn activity was approximately 1 μCi . Each sample was then counted in 4000-second time bins until the well known 847 and 1811 keV ^{56}Mn γ -ray lines disappeared into the background. From measurements on these individual sources, the composite decay curves shown in Fig. 1 were constructed. The

slopes of the lines drawn through the data represent the known 2,5785-hour ^{56}Mn half-life.

Least squares fits to these data were made assuming a) purely exponential behavior and b) a number of theoretically suggested alternative forms of the decay law. The results of all of these fits show that our data are consistent with purely exponential behavior out to the limit of our measurements, ~ 42 half-lives. This represents an extension of about 8 half-lives over the most sensitive previous search of this type.⁵

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Fig. 1. Composite decay curves for the 847 and 1811 keV γ -rays obtained from the ^{56}Mn sources described in the text. The slope of the straight lines through the data points represents the known 2.5785 hour ^{56}Mn half-life.

XBL 8510-9584

Correlation Properties of Unresolved Gamma Rays From High Spin States*

J.E. Draper,[†] E.L. Dines,[†] M.A. Deleplanque, R.M. Diamond, and F.S. Stephens

Evidence is accumulating that the rotational behavior of nuclei at the highest spins differs significantly from that which is familiar for lower spin states. It has been known for some time that the γ -ray spectra following heavy ion fusion reactions consist of both resolved and unresolved parts. The resolved lines have been intensively studied and are emitted after the population has condensed into the lowest few (cold) states of each spin. In the rare earth nuclei, such lines are seen from states having spins as high as about $45\hbar$, and carry most of the population below spins of $20\text{--}30\hbar$. The rest of the spectrum is composed of unresolved lines which are thought to be emitted while the population is spread over very many states prior to condensing into the lowest few. Thus it presumably occurs at non zero temperatures where the level density is high. It is possible to study the general properties of these unresolved γ rays, and the evidence is rather convincing that most of them are rotational type transitions. On the other hand there should be strong correlations among the γ -ray energies in rotational bands, and these are found to be either much weaker or absent in the unresolved spectra. An important objective of high-spin physics is to learn more about the correlations remaining and to determine whether the modified rotational behavior is due to the high level density in which the bands are thought to be located, or, if not, what causes it.

The present experiments are aimed at better defining the nature of the rotational correlations in the unresolved spectra. These are displayed in plots of coincident γ -ray energies, $E_{\gamma 1}$ vs $E_{\gamma 2}$, called correlation plots.¹ The main characteristics are a valley along the diagonal of the plot ($E_{\gamma 1} = E_{\gamma 2}$) and ridges that sometimes occur on either side of this valley. These "rotational correlations" result from the properties of a "good" rotational band, $E_{\gamma} \approx 2I\hbar^2/\mathcal{I}$ where the difference between $E_{\gamma}(I+2 \rightarrow I)$ and $E_{\gamma}(I \rightarrow I-2)$ is a constant (giving the ridges) related to the moment of inertia $\mathcal{I}$ and no two γ rays ever have the same energy (giving the valley). Attenuation of

these correlations implies that the transition energies within any particular band are not so regular as those in a "good" rotor. The effect of such irregularities is first to wash out the ridges and, as they increase further, to broaden and fill in the valley. The extent of the irregularities can be expressed as a width σ_{γ} of a Gaussian probability distribution for the γ -ray energies emitted by each rotational state. The normal sharp rotational energies result when σ_{γ} is equal to zero. To determine σ_{γ} we devised an experimental method to measure independently the width and depth of the valley at any particular γ -ray energy. The width is closely related to σ_{γ} and the depth to both σ_{γ} and the fraction of cascades having such properties. Results have been obtained for several γ -ray energy regions in ^{160}Er , using the reaction $^{124}\text{Sn}(^{40}\text{Ar}, 4n)^{160}\text{Er}$ with 185 MeV ^{40}Ar ions from the LBL 88-Inch Cyclotron.

The experimental results (the full width at half maximum rather than σ_{γ} is given) are shown in Table I. Below about 900 keV the widths are small and comparable to the NaI resolutions (whose effect has been removed from all values in Table I), and thus only a limit is given; however the accuracy of the higher-energy points is rather good. Surprisingly,

Table I
Experimental Results

γ -ray energy region	δ	FWHM $_{\gamma}$
720	$0.09 \pm .02$	<40
840	$0.09 \pm .02$	<40
960	$0.14 \pm .03$	90 ± 15
1080	$0.12 \pm .03$	70 ± 15
1200	$0.17 \pm .03$	125 ± 20

only 10–20% of the population (δ) contributes to this width. At the lower energies there could be a significant contribution from known resolved lines, but at the higher energies these are much too weak to affect appreciably the observed results. Since this is the first experiment to evaluate σ_γ and δ simultaneously, it is the first indication of more than a single γ -ray spreading width. The measured width can possibly be interpreted as due to the high level density;² however, the broad spreading of most of the population (80–90%) is still a puzzle.

Structural Changes in ^{156}Er at High Spins*

F.S. Stephens, M.A. Deleplanque, R.M. Diamond, A.O. Macchiavelli, and J.E. Draper†

Transitional nuclei, between the double-closed shell $N=82$, $Z=64$ and the deformed nuclei, $N \approx 90$, $64 < Z \leq 70$, have received considerable attention recently. There are several interesting properties expected in these nuclei. At very high spins ($\geq 50\hbar$) superdeformations are predicted and evidence for them has been seen¹ in correlation plots of the unresolved spectra of ^{152}Dy . At spins below $40\hbar$ there is known to be a competition among several shapes: approximately spherical, weakly deformed oblate, and moderately deformed prolate. However, in many of the nuclei the shapes are poorly known, if at all, and in no case is much detail on any shape change available.

The present data on ^{156}Er represent the first results from the Berkeley High Energy-Resolution Array (HERA), a system that will consist of 21 Compton-suppressed germanium (CSG) detectors, together with a $\sim 4\pi$ central ball to measure total γ ray energy and multiplicity.² The ^{156}Er was produced as the $4n$ product resulting from bombardment of ^{120}Sn with ^{40}Ar projectiles at several energies, but mainly at 170 MeV. The ^{120}Sn targets were about 1 mg/cm^2 thick on lead backing. This backing stopped the recoiling Er nuclei in $\sim 1\text{ psec}$. It was found that all the resolved γ ray lines were emitted after stopping, resulting in no Doppler shift or

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- † University of California, Davis, California 95616.
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broadening. This is due to the long feeding times in transitional nuclei, and improved the resolution from 3–4 keV (when thin targets were used) down to $\sim 2\text{ keV}$. However, no delayed transitions were observed in this nucleus with lifetimes longer than $\sim 20\text{ nsec}$, the electronic resolving time used in this experiment.

The level scheme for ^{156}Er was constructed from the coincidence data and is shown in Fig. 1. It consists of nearly 100 levels, connected by about 130 γ rays, which form 5 bands and pieces of 2 or 3 other bands. The lower part ($I \lesssim 30\hbar$) of the scheme is clearly rotational, resembling the heavier rare-earth nuclei. The lowest levels are probably weakly deformed prolate but soft toward deformation. Under rotation they appear (from the level spacings) to stretch out to typical deformations ($\epsilon \sim 0.2$ – 0.25) by spin 8 or 10, as is seen for other nuclei in this part of the transition region.³

A new feature observed in bands 3, 4, and 5 is the abundance of interband transitions at the backbends, around spin 22. All three of the bands (and some other levels) participate in this cross feeding. It suggests that the integrity of the bands, as indicated by a single predominant $B(E2)$ value for the decay of each state, is broken. This is known to happen sometimes at band crossings due to mixing of the

two bands, but in the present case bands having different signatures are involved, requiring a more general explanation. This suggests to us that the structure changes across this region, and during the reorganization band integrity is weakened. The nature of the change seems very likely to be related to the backbend, since the cross feeding occurs exactly at that point. This backbend involves the third and fourth quasineutrons in ^{156}Er and it is reasonable that these quasineutrons could cause a large reduction or collapse of the neutron pairing which in turn might cause some change in shape. This seems to us a consistent explanation for the observed behavior.

Perhaps the most interesting feature of the ^{156}Er level scheme is the structure between the 9.6 MeV, 30^+ , and the 14.4 MeV 42^+ levels. The 42^+ level is almost undoubtedly the fully aligned configuration $\pi(h_{11/2})_6^4 \nu(h_{9/2})_8^2 (f_{7/2})_6^2 (i_{13/2})_{12}^2$ (relative to a ^{146}Gd core), consistent with an approximately oblate shape. However, the backbone of this structure (the 387–1368 and 704–918 branches are weak) is a sequence of six successive stretched E2 transitions. We take this as evidence for some collectivity in the region. An interpretation consistent with all this evidence, as well as current theoretical calculations, is that this is a triaxial band terminating in the (nearly) oblate fully aligned 42^+ state.

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Fig. 1. Level scheme of ^{156}Er .

XBL 855-2524

Slow and Fast High-Spin Sequences in ^{158}Er *

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M.A. Deleplanque, J.E. Draper,‡ and F.S. Stephens*

Calculations¹⁻³ predict that in the nucleus ^{158}Er oblate shapes will compete with prolate and triaxial ones along the yrast line near spin $50\hbar$; the first oblate shape predicted to be on the yrast line is the fully aligned 46^+ state.

$\pi[(h_{11/2})^4]_{16} \nu[(f_{7/2})^3(h_{9/2})^2(i_{13/2})^2]_{30}$. Experimental evidence has recently been reported⁴ for a change to oblate shape, however, at somewhat lower spin, $\sim 40\hbar$. The present letter describes some of the first results obtained with HERA, the High Energy Resolution Array⁵ at Berkeley, for the nucleus ^{158}Er .

The reaction used was $175\text{ MeV } ^{40}\text{Ar} + ^{122}\text{Sn}$; the beam was provided by the LBL 88-Inch Cyclotron. A part of the spectrum (700–1400 keV) obtained with thin unbacked targets in coincidence with the 1058 keV ($38^+ \rightarrow 36^+$) transition is shown in the upper part of Fig. 1. The five highest transitions observed in ref. 4 of 827, 1031, 1203, 1210, and 1280 keV can be seen, and in addition there is a weak 971 keV line. The lower part of the figure shows the same region gated by the same transition, but for a gold-backed target; it is clear that the 1203–1210 keV lines are missing. We believe these are not observed because they are smeared out by Doppler shifts arising from the spread in velocity of the emitting nucleus as it slows down and the variety of detector angles relative to the beam direction. The mean time to slow the recoiling ^{158}Er nucleus in gold (lead) can be estimated from range-energy data to be around 0.5 (1.0) picosecond. For the 827, 971, 1031, and 1280 keV transitions to be sharp in the lower figure means that they must have been emitted after an interval (corresponding to their lifetime plus feeding time) 2–3 times longer than this ($>2\text{ ps}$). The fact that the 1200 keV lines disappear in that figure means that they have lifetimes (plus feeding times) shorter than the mean slowing time ($<0.5\text{ ps}$).

Coincidence spectra show that the 1280 keV transition is not in coincidence with the 1203 and 1210 keV transitions, but is in coincidence with the

Fig. 1. Coincident gamma-ray spectra from the reaction $^{122}\text{Sn}(^{40}\text{Ar},4n)^{158}\text{Er}$. Upper: Transitions in coincidence with a gate on the 1058 keV γ -ray depopulating the spin 38^+ level, self-supporting target. Lower: Transitions in coincidence with the same gate, but gold-backed target. XBL 855-2515

827, 1031, and 971 keV gamma rays. Similarly, they show that the 1203 and 1210 keV gamma rays are *not* in coincidence with the 827, 971, 1031, and 1280 keV transitions but do feed in at the 38^+ level and are in coincidence with each other. Their relative intensities suggest that the 1203 keV line is the lower. The 971–1031–1281–827 keV cascade is ordered on the basis of relative intensities, though the nearly equally intense 827 and 1280 keV transitions might possibly be reversed. The gamma-gamma angular correlation data indicate that the 827 and 1280 keV lines are stretched E2 transitions, and that the 1031 keV line is too. The other high-spin transitions were

Fig. 2. Top of the level scheme for the yrast band in ^{158}Er .
XBL 855-2513

too weak to determine reliably, but we believe that the 971 keV line might well be a stretched E2 also. The top part of the level scheme determined here is shown in Fig. 2.

One of the two interesting results of these experiments is the identification of fast and slow feeding components into the 38^+ state of ^{158}Er . Such components have been seen separately in neighboring nuclei and have generally accepted interpretations. Among the Gd, Dy, Er, and Yb ($64 \leq Z \leq 70$) nuclei, those having neutron numbers between 82 and 88 generally have slow feeding times (< 1 psec). The reason is thought to be that they have regions of non-collective behavior (oblate or spherical shapes) along the decay pathways. Such regions have relatively slow transitions (of order single-particle strength or less) and no smooth decay pathways. In contrast, the well deformed rare-earth nuclei ($64 < Z < 74$; $90 < N < 110$) have fast feeding times ($\ll 1$ psec), thought to be due to the presence of rotational bands. These bands provide smooth pathways of strongly enhanced E2 transitions, and thus

provide for rapid de-excitation. It is therefore not so surprising that ^{158}Er , which lies on the boundary between these regions, would have both fast and slow feeding components, but we have been able to identify resolved lines in each of these two branches and to determine how they feed into the known yrast sequence.

The other major point of interest in these results is the nature of the highest spin state found, that decaying by the 971 keV transition. If the 971 keV line is a stretched E2 transition, this state is the 46^+ that is the maximally aligned state predicted by theory.^{1,2} That is, it is a band termination and has all the valence particles aligned to their maximum spin, producing an oblate nucleus ($\gamma=60^\circ$). Higher spins would have to be made by core excitation or by promoting the valence particles to the next shell.

The data provide the best evidence to date that there is a change to oblate shapes at high spin for some states in ^{158}Er and very probably to the maximally aligned 46^+ state. At the same time it shows that there are also decay pathways that do not go through such shapes. Perhaps most importantly, it gives us experimental access to study separately resolved lines associated with the two types of feeding.

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A New Upbend in $^{159}\text{Er}^*$

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The nucleus ^{159}Er was made as a 5n product in the reaction $^{124}\text{Sn} + ^{40}\text{Ar}$ at 180 MeV at the 88-Inch Cyclotron. Twenty Compton-suppressed germanium detectors of the High-Energy-Resolution Array (HERA) were used, collecting about 10^8 triple events in a day. The correlated spectrum at high resolution (1 keV per channel) has been used in the initial search for clean gates since such gated spectra are already background subtracted and display the transitions most correlated with the gate. Bands 2, based on the E neutron state $(-, +1/2)$, and 4, based on the F neutron state $(-, -1/2)$, have been extended at high spins, as compared to ref. 1. In band 2 an upbend is found at spin $\sim 77/2\hbar$ and at a frequency of 0.55 MeV where at least three transitions around 1110 keV are found in coincidence, bringing at least six units of aligned angular momentum. The relative order of these transitions is not certain. It seems most likely to us that the aligned proton orbitals from the next empty shell ($h_{9/2}$, $i_{13/2}$) are populated at this frequency, since the main alignments of the valence shell have been exhausted. Another interpretation has been recently suggested² for these $81/2^-$ and $85/2^-$ states in band 2: they would be low in energy because they are formed by almost fully aligned (nearly oblate) configurations which are calculated to be energetically favored in that spin and mass region.

A lot of information is beginning to be available at high spins in this region of nuclei, which promises to give a better understanding of the different possibilities.

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Fig. 1. Partial level scheme of ^{159}Er . The spins should be considered tentative. XBL 853-1895

Lifetime Measurements of High Spin States in ^{166}Yb .*

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Recently an increasing amount of effort has been focused on studying "good" rotational nuclei at high spin. The present high resolution and highly efficient detector systems, obtained by using a large number of Germanium detectors in compact geometry, have enabled us to observe discrete line states typically to spin $40\hbar$.^{1,2} In the region of well deformed nuclei all present data seem to indicate that rotational bands exist up to these high spins since the expected $\hbar^2/2\mathcal{I} I(I+1)$ sequences of states have fairly constant values of $\mathcal{I}$ (the kinetic moment of inertia).² But the only way to ascertain whether collectivity has survived the coriolis and rotational alignment effects expected at these high rotational velocities is to measure the transition quadrupole moments of these high spin states, i.e., their lifetimes.

The present letter describes results obtained with HERA,³ the High Energy Resolution Array at Berkeley. The nucleus ^{166}Yb was investigated by bombarding 180 MeV ^{40}Ar ions on thin (gold backed and unbacked) targets of ^{130}Te at the 88-Inch Cyclotron. For the first time it was possible to perform line shape analysis of transitions in coincidence with discrete line gates from which the high spin background was subtracted. This technique greatly reduces the background and cleans the resulting spectra, providing large areas to be fitted. We find that the yrast states have large collective $B(E2)$ values all the way up to spin 34 and that the feeding pathways, presumably rotational side-bands lying higher in excitation energy, have on average $B(E2)$ values smaller by a factor of 3. From the line shape of the top transitions the presence of isomeric states on the pathway feeding the yrast high spin states would be detected and those states excluded. The yrast states are fed by a large number (5–7) of gamma rays with fast transition probabilities consistent with normal collective rotational transitions. In the present data the limiting factor in extracting lifetimes of even higher spin states was statistics. The method could

have been used to spin 44–42 transitions (in which case the feeding time is short and the peaks are fully Doppler shifted) if the extra transitions kept the same collective character. The sum of three discrete line gates (569 + 509 + 588 keV peaks) were used to produce the background subtracted spectrum shown in Fig. 1. The line shape of the peaks above the 667 keV line shows clearly the shoulders created by lifetimes plus feeding times which are in the range of the mean slowing down time in gold (0.5 picoseconds). Two statements can be made by inspecting the line shape of the top transitions. The top-most transition, $32^+ \rightarrow 30^+$, in Fig. 1 has a sharp and symmetrical line shape and its centroid shows only a Doppler shift of 11 keV instead of the expected 18.5 keV for the full Doppler shift. Therefore, transitions preceding this state must be fast (excluding the possibility of isomerism feeding this state at higher spins and temperatures) and numerous, since one requires a step delay (not exponential) in the feeding time distribution. The line shapes below spin 30 have two well-defined peaks, implying that the side-feeding into these states is different from the in-band feeding. From the intensities of the two peaks it is in-

Fig. 1. Background subtracted spectrum for the four forward Germanium detectors. Thick line obtained from the D.S.A.M. fit.

XBL 8510-4329

ferred that the side-feeding has the slow time component. Using the same reasoning as above, the side-feeding population does not seem to be compatible with isomeric transitions.

To study the lifetimes involved in the transitions from 34^+ through 22^+ states, a simple Doppler Shift Attenuation program was developed. The model has a rotational band with the known yrast discrete line energies and a set of transitions preceding the top known transition. The side-feeding to each spin state could be either prompt or provided by a rotational side-band with its own quadrupole moment. In this way both the yrast in-band lifetime and the side-band feeding times were fitted at each spin individually. The slowing down process through the backing was considered to be exponential with a mean slowing down time characteristic of ^{166}Yb in Au (0.5 picoseconds). The data were then fitted for all eight angles available in the experimental setup. The fits obtained at forward angles can be observed in Fig. 1. Table I contains a resume of the fitting parameters for all angles and the individual χ^2 for each peak fitted. The errors in the lifetimes and

feeding times obtained in such a fit are small, since the number of data points greatly exceeds the number of free parameters in the fit. The covariances between the side-feeding times and in-band lifetimes were found to be small and we therefore believe that the largest source of error comes from systematic errors, such as that in the mean slowing down value used and the assumption of an exponential slowing down process.

Table I gives both lifetimes and $B(E2)$ values. A tendency for a loss of collectivity towards higher spins (as can be inferred from the decreasing $B(E2)$ values) is observed but nevertheless even at 34^+ the nucleus seems to retain a large portion of the deformation with which it started. The decrease in $B(E2)$ values can occur both from decreasing the e_2 deformation or from going toward triaxial shapes (non-zero γ -degree of freedom), as can be seen from the relation $B(E2) \propto e_2^2 * \cos(30+\gamma)$.⁴ The side-bands which feed the yrast states (assumed to be at larger temperatures) have nevertheless smaller $B(E2)$ values showing even smaller collectivity (larger γ -value or smaller e_2). We point out at this stage that these

Table I ^{166}Yb Yrast Transition from Fit Program

E_γ	$I \rightarrow I-2$	Side-feed %	χ^2 ^{a)}	τ psec $\times 10^{-2}$	$B(E2)$ ^{b)}	$B(E2)_{\text{SB}}^{\text{c)}$
1112.2	$36^+ \rightarrow 34^+$	50	2.4			
1060.0	$34^+ \rightarrow 32^+$	50	2.9	5 ± 1	120^{+29}_{-19}	120
998.8	$32^+ \rightarrow 30^+$	40	2.2	6 ± 1	134^{+25}_{-19}	60
935.5	$30^+ \rightarrow 28^+$	30	2.8	7 ± 1	159^{+27}_{-10}	40
870.2	$28^+ \rightarrow 26^+$	26	2.5	10 ± 1	160^{+18}_{-15}	80
805.8	$26^+ \rightarrow 24^+$	20	4.2	12 ± 1	196^{+18}_{-15}	<60
738.6	$24^+ \rightarrow 22^+$	30	4.0	19 ± 2	192^{+22}_{-19}	<60
666.3	$22^+ \rightarrow 20^+$	20	3.8	32 ± 4	190^{+27}_{-21}	<60

a) Average over all eight angles

b) $B_W(E2) = (2\lambda + 1) \frac{1.2^2}{4\pi} \left(\frac{3}{2}\right)^2 A^{4/3} \langle \max \rangle^2 e^2 \text{fm}^4$ where $\langle \max \rangle^2 = 0.375$.

c) Errors are of the order of 20% in all these values. These should be considered as upper limits for reasons given in text.

side-band Qo's are only an upper limit since prompt feeding to these bands coupled to slower in-band transitions could reproduce the side-feeding time profile equally well and that possibility was not taken into account in the model. Although the continuum gamma-rays feeding these yrast states are not expected a priori to be any different from the bulk of the continuum, they only represent 30 percent of all unresolved gamma-rays. The present data also contain information on the lifetimes of the continuum gamma-rays emitted from the highest temperature and spin regions. The direct analyses of these transition lifetimes will complement nicely the present results and we hope give us an insight into the rotational nucleus collectivity over a range of temperatures for these very high rotational frequencies.

Levels in Alpha Decay of ^{257}Md to ^{253}Es

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During a recent collaborative experiment with E.K. Hulet *et al.* at the 88 Inch Cyclotron, a target of ^{254}Es was bombarded with $^{22}\text{Ne}^{+5}$ (125 MeV on target) for approximately four hours. Recoiling products were caught on a catcher foil placed downstream of the target. At the end of the run the catcher foil was removed and flown to Livermore via helicopter. The products were mass-separated, and the mass 257 fraction was driven back to LBL for alpha pulse height analysis.

The $A=257$ fraction was counted repeatedly over the course of ten days. Approximately 670 events attributable to the alpha decay of ^{257}Md were observed.¹⁻³ Most of the ^{257}Md events were contained in a peak at 7.073 MeV and decayed with a half-life of 5.6 hours ($\pm 15\%$). We were also able to observe a second smaller peak at 7.040 MeV which was roughly 20–25% of the major peak. Q_α was estimated⁴ to be 7.504 MeV, and this gives α_{max} as 7.387 MeV. This leads us to believe that ^{257}Md decays primarily to a $7/2^- [514]$ state in ^{253}Es with about 20% going to the $9/2^- [514]$ rotational level 33 keV above the bandhead. The bandhead itself is 314

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Fig. 1. Decay of ^{257}Md .

XBL 8510-4334

keV above the $7/2^- [633]$ ground state of ^{253}Es , which is somewhat analogous to the decay of ^{255}Md .

A second smaller peak indicative of a rotational level about 70 keV above the bandhead was seen at 6.99 MeV. However, another peak at 7.01 MeV obscured this peak and thus precludes a definite as-

signment for these peaks at this time. Similarly, no observations of any spontaneous fission events from the ^{257}Md could be obtained because of spillover in the mass separator of ^{256}Fm . Approximately 60 fission events were observed with a half-life of $4 (\pm 2)$ hours, so these effectively masked any ^{257}Md fissions that might have been present.

Future studies of this decay will probably require a chemical separation to isolate the ^{257}Md even further, and possibly alpha-gamma correlation spectroscopy.

Modeling Actinide Production Cross Sections from Heavy Ion Transfer Reactions

K.E. Gregorich

A modeling procedure has been developed for the actinide production cross sections from damped transfer reactions between very heavy ions and actinide targets. These reactions are assumed to proceed via the formation of a dinuclear complex consisting essentially of touching target-like and projectile-like fragments which can exchange nucleons and energy. In this model, the $d^2\sigma/dZdE$ distribution (where E is the kinetic energy damping) is given by the empirical description of Wollersheim.¹ Many studies have shown that the N/Z ratios in the target-like and projectile-like fragments of the dinuclear complex equilibrate rapidly. In this model, it is assumed that the N/Z ratios are fully equilibrated and that this equilibration comes about by exchange of neutrons between the two fragments in the dinuclear complex. It is also assumed that the equilibration of the distribution of excitation energy between the two fragments is complete. This equilibration is carried out, in the model, by calculating the dinuclear complex level density for every possible distribution of neutrons and excitation energy between the two fragments for each element of the $d^2\sigma/dZdE$ distribution. Distributing the cross section according to these level densities yields the initial (before deexcitation) distribution of target-like fragments,

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$d^3\sigma/dZdNdE^*$. This initial distribution is then allowed to deexcite by a standard angular momentum independent Γ_n/Γ_f calculation to yield a final $d^2\sigma/dZdN$ distribution.

The results of the calculation for 870 MeV $^{136}\text{Xe} + ^{249}\text{Cf}$ are presented in Fig. 1. The elemental distributions for $Z > 98$ fall off rapidly with increasing Z . For $Z < 98$ the elemental distributions fall off more slowly with decreasing Z , reach a minimum at $Z=92$, and then increase. It can be seen that the $N=82$ closed shell in the projectile-like fragment ($N=151$ in the target-like fragment) has a strong effect on the calculated cross section distribution. These general trends are apparent in the experimental cross sections from this reaction.² Although the experimental cross sections for $Z < 93$ were not measured for the $^{136}\text{Xe} + ^{249}\text{Cf}$ reaction, an increase in the cross section with decreasing Z below $Z=92$ was observed in other heavy ion bombardments of actinide targets such as $^{48}\text{Ca} + ^{248}\text{Cm}$.³ It is apparent that this modeling procedure reproduces the general features of the final cross section distribution.

In order to examine the more specific features of the calculated cross section distribution, a comparison of the calculated and experimental cross sec-

Fig. 1. Calculated cross section distribution from 870 MeV $^{136}\text{Xe} + ^{249}\text{Cf}$. XBL 858-3250

tion distributions from the 870 MeV $^{136}\text{Xe} + ^{249}\text{Cf}$ reaction is presented in Fig. 2. It can be seen that the calculated heights of the cross section distributions are close to the experimental values and for all but the Am distributions, the centroids and widths of the calculated elemental cross section distributions are essentially correct. In summary, the general features of damped heavy ion transfer reactions in the actinide region are predicted by this model, but refine-

Fig. 2. Comparison of calculated and experimental cross sections. XBL 858-3248

ments will have to be made before the prediction of cross sections for the transfer of a large number of nucleons can be made accurately.

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Production of Below Target Elements in the Reactions of ^{248}Cm with ^{48}Ca and ^{40}Ca Projectiles

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Yields for isotopes with atomic numbers smaller than that of the target were measured for the reactions of ^{248}Cm with ^{40}Ca and ^{48}Ca projectiles with energies from near the Coulomb barriers to 60 to 80 MeV above the barriers. We have previously reported on the yields for the transcurium element isotopes from these reactions.¹ The maxima of the mass-yield distributions for the transcurium elements were only about 2 mass units larger for the ^{48}Ca than for

the ^{40}Ca reactions; thus the 8-neutron difference in the projectiles is only partially reflected in the heavy product yields. The excitation functions for production of these transcurium isotopes were measured and found to be near their maxima at the Coulomb barrier for the ^{40}Ca reactions, consistent with the calculated positive excitation energies for these reactions. However, the observation that the yields decreased only slowly with increasing projectile energy

was somewhat surprising because the fission barriers are only of the order of 5 to 6 MeV. Apparently only a small fraction of the projectile kinetic energy appears as excitation energy of the heavy product. We wished to measure the yields for products lighter than the target to learn more about the reaction mechanisms for these reactions and to ascertain whether such reactions might also give access to exotic neutron rich isotopes of the lighter actinides.

The measured mass-yield curves for some of the lighter than target elements from the reaction of ^{48}Ca with ^{248}Cm are shown in Fig. 1. The cross sections are remarkably high with maxima of the order of 200 microbarns or more for elements down to Rn ($Z=86$). The half-widths of these isotopic distributions are 4.5 to 5 mass units, considerably larger than those observed for the above target distributions. Yields were measured for only a few isotopes of Th, U, and Pu for the ^{40}Ca reactions, but the yields were much lower than for ^{48}Ca and in many cases only upper limits could be set on the cross sections. A comparison of the integrated elemental yields for ^{40}Ca and ^{48}Ca is shown in Fig. 2. As can be seen, the yields of the below target elements are lower by factors of 10 to 100 for the ^{40}Ca reactions. This may be a result of the tendency toward N/Z equilibrium in which protons would tend to flow from the proton rich ^{40}Ca to the neutron rich (proton deficient) ^{248}Cm .

The data for the yields of Th, Ac, and Ra from the ^{48}Ca reactions suggest the formation of the very neutron rich Fe, Co, and Ni isotopes, ^{65}Fe , ^{68}Co , and ^{72}Ni , as complementary fragments (assuming emission of only one neutron from the light fragment) with similar cross sections of the order of 200 microbarns.

Additional studies of the yields of below target isotopes from the reaction of ^{40}Ca with ^{248}Cm are in progress to try to measure the yields of more isotopes and to increase the sensitivity of the measurements. Similar studies for reactions of ^{248}Cm with ^{16}O and ^{18}O have been initiated to see if the yields of below target isotopes will be similarly low.

Fig. 1. Mass-yield distributions for some lighter than target elements from the reaction of ^{48}Ca with ^{248}Cm .
XBL 8412-13509

Fig. 2. Comparison of elemental yields for ^{40}Ca and ^{48}Ca reactions with ^{248}Cm .
XBL 851-942

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Excitation Functions for the Production of Heavy Actinides from the Interaction of ^{16}O with ^{249}Cf

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The cross sections for the production of heavy actinides from the reaction of ^{16}O with ^{249}Cf have been measured. A californium oxide target containing 0.334 mg/cm^2 ^{249}Cf was bombarded at the 88-Inch Cyclotron with 89.5, 96.1, 106.1, 114.8, 122.7, 138.4, and 150.5 MeV ^{16}O projectiles. (All quoted energies have been corrected for energy losses in the Havar entrance window, cooling gas, and Be target backing.) The heavy actinide products recoiling out of the target were stopped in 1.5 mg/cm^2 gold catcher foils. The actinides were chemically separated from the gold and rare earth contaminants, then finally separated from each other by elution from a cation exchange resin column with ammonium alpha-hydroxyisobutyrate. The individual chemical fractions were evaporated onto platinum foils and counted for gamma, alpha, and spontaneous fission activities. From the counting data and the beam histories from the individual bombardments the cross sections for the elements Bk through Fm were determined.

The excitation functions for the production of Es and Fm isotopes are shown in Figs. 1 and 2. The maxima of the curves for $^{249},^{250},^{251}\text{Es}$, are all slightly above the Coulomb barrier of about 97 MeV, consistent with their calculated excitation energies of -1.3 , 1.9 , and -2.7 MeV, respectively. (Data for ^{252}Es and ^{253}Es are still being analyzed.)

Similarly, for the Fm isotopes the maxima of the excitation functions are all very close to the Coulomb barrier, except for ^{256}Fm whose maximum is about 10 MeV higher. However, the cross sections for the Fm isotopes decrease much more rapidly with increasing energy than for the Es isotopes, consistent with the more positive excitation energies for ^{251}Fm through ^{253}Fm . The maxima of the excitation functions for ^{245}Bk and ^{246}Bk are also about 10 MeV above the barrier, consistent with their calculated excitation energies of -5.4 and -7.0 MeV. However, their cross sections decrease only very slowly over the energy range of 60 MeV which we studied, indi-

Fig. 1. Excitation functions for production of Es isotopes. (Data for ^{252}Es and ^{253}Es are still being analyzed.) The errors shown in the figure are the statistical standard deviations based on the decay analysis of the measured radiations. In addition, the estimated standard deviation due to uncertainties in the absolute detection efficiencies, target uniformity, current stability and integration and chemical yield is 12%.
XBL 8511-4557

Fig. 2. Excitation functions for production of Fm isotopes.
XBL 8511-4558

cating that this additional kinetic energy must not be manifested in excitation energy of these Bk isotopes or they would have been lost by prompt fission. The maximum cross section for the peak of the Bk mass-

yield distribution at mass 246 was only 160 microbarns, much lower than the maximum of 10,000 microbarns observed for Es and 4000 microbarns observed for Fm.

Comparison of the Excitation Functions for the Production of Heavy Actinides from Interactions of ^{16}O and ^{18}O Projectiles with ^{249}Cf .

D.C. Hoffman, D.M. Lee, K.E. Gregorich, R.M. Chasteler, R.A. Henderson, M.J. Nurmia, and G.T. Seaborg

Analysis of data for the production of actinides from ^{16}O reactions with ^{249}Cf has recently been completed. Data for the production cross sections of actinides from the reaction of ^{18}O with ^{249}Cf were published earlier.¹

As seen before with this type of reaction, products corresponding to the transfer of a few nucleons have the highest cross sections. The cross sections drop off rapidly with increasing number of nucleons transferred. The maximum yields for isotopes of Bk which has one proton less than the target are of the order of 50 more than for Es which has one proton more than the target.

A comparison of the yields for Es and Fm isotopes at the maximum of their excitation functions from ^{16}O and ^{18}O reactions with ^{249}Cf is shown in Fig. 1. In contrast to our results for ^{248}Cm , the shift in the maxima of the mass-yield distributions between ^{16}O and ^{18}O is one or less instead of two mass units. The half-widths for the mass distributions from the ^{249}Cf target are about 1.5 mass units compared to about 2.5 mass units measured earlier^{1,2} for ^{248}Cm .

The peak production cross sections for the Es isotopes occur at about the same energies for both ^{16}O and ^{18}O reactions with ^{249}Cf as expected. The peak production cross sections for Fm isotopes from the reactions of ^{249}Cf with ^{16}O occur at an energy very close to the Coulomb barrier, whereas the peak for the ^{18}O reactions is about 7 MeV above the barrier. Since the excitation energies for products from transfer of the same nucleons is about the same for both ^{16}O and ^{18}O reactions, this would not have

Fig. 1. Comparison of the mass-yield curves for Es and Fm at the maximum of the respective excitation function for each isotope taken from Figs. 1 and 2 of the previous paper in this Annual Report.

XBL 8511-4555

Fig. 2. Comparison of the yields of Fm isotopes from ^{249}Cf and ^{248}Cm targets with ^{16}O projectiles at energies near the Coulomb barrier.

XBL 8511-4556

been expected.

A comparison of the Fm yields from ^{16}O reactions with ^{249}Cf and ^{248}Cm targets is shown in Fig. 2. As observed before for ^{18}O reactions, the maximum cross section is about 1000 times that for ^{248}Cm , but for the more neutron-rich isotope ^{256}Fm the yields

are nearly the same. Presumably for still more neutron-rich Fm isotopes the yields would be greater for the ^{248}Cm target.

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Fast and Slow Processes in the Fragmentation of ^{238}U by 85 MeV/nucleon ^{12}C

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During the past year we completed our measurements of the angular distributions of 48 different target fragments in the interaction of intermediate energy (85 MeV/nucleon) ^{12}C with ^{238}U . This study was intended to complement our previous study of the fragment angular distributions in the reaction of 85 MeV/nucleon ^{12}C with ^{197}Au .¹

Representative laboratory frame angular distributions for the ^{238}U reaction system are shown in Fig. 1. The typical light fragment distribution (^{46}Sc) has a forward-peaked distribution. The typical "average" fission fragment (^{99}Mo) distribution is less forward-peaked than the light fragment distribution but is not isotropic. The heavy fragment distribution (^{146}Gd) is very strongly forward-peaked. For the ^{238}U reaction system, the angular distributions are less forward-peaked than for the ^{197}Au reaction system, consistent with previous observations² of lower momentum transfer in U target fragmentation.

These laboratory frame angular distributions were transformed into the moving frame of the target residue following the initial projectile-nucleus encounter (Fig. 2a). The parameter $\eta_{\parallel} = (v_{\parallel}/V)$ used to make the transformation (where $v_{\parallel}$ is the longitudinal velocity of the moving frame and V is the velocity of the fragment in the moving frame) was determined from integrating the angular distributions to give F and B , the fraction of fragments recoiling forward and backward from the target [$\eta_{\parallel} = (F-B)/(F+B)$]. The

Fig. 1. Representative target fragment laboratory frame angular distributions for the reaction of 85 MeV/nucleon ^{12}C with ^{238}U . XBL 8510-4152

resulting average fission fragment distributions are symmetric about 90° in the moving frame, indicative of a "slow" process in which statistical equilibrium has been established. The light fragment distributions are asymmetric in the moving frame indicative

of their production in a "fast" process without the establishment of statistical equilibrium. For the U reaction system the heaviest fragments ($A=139-169$) also had moving frame distributions that were asymmetric, indicative of a "fast" production mechanism.

In view of the observation of Lynen *et al.* that the production of light fragments was a binary process at these projectile energies, we thought it would be interesting to see if we could find, among our data, the heavy fragment complements to these light fragments. We show (in Fig. 2b) the general similarity between the ^{146}Gd moving frame distribution and the calculated distribution for the complementary fragment to ^{46}Sc . It would be fortuitous in an experiment such as we have performed to find among the half dozen or so heavy fragments, whose angular distribution we have measured, the exact kinematic complement of light fragment distribution. Furthermore, a single-particle inclusive experiment such as this is not the best way to look for kinematic complementarity. Nonetheless, the similarity between the ^{146}Gd distribution and the calculated " ^{46}Sc -complement" distribution is quite striking. Further support for this idea comes from the isobaric yield distribution for this reaction³ where the $A=46$ and $A=146$ fragments occupy approximately complementary positions in the fission-like portion of the mass yield curve, and the $v_{\parallel}$ values of $A\sim 50$ and $A\sim 150$ fragments which are consistent with complementarity.

Thus it becomes interesting to speculate that we may have observed a new intermediate energy heavy ion reaction mechanism, a "fast," non-equilibrium, very asymmetric fission. (The actual process could very well be characterized by a very broad symmetric mass distribution that is "hidden" under the more abundant average fission distribution and only becomes visible to us in the low and high mass tails of the distribution.)

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Fig. 2a. Moving frame angular distributions for the fragments shown in Fig. 1. XBL 8510-4153

Fig. 2b. A detailed comparison of the ^{146}Gd fragment moving frame angular distribution and that calculated for the heavy fragment complement of ^{46}Sc . XBL 8510-4150

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Target Fragment Energy Spectra in the Interaction of 49 MeV/nucleon and 85 MeV/nucleon ^{12}C with ^{197}Au

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The reaction mechanism(s) responsible for the formation of light fragments ($A_{\text{frag}} < A_{\text{target}}/3$) in heavy ion-heavy nucleus collisions have not been clearly identified. In addition to measuring the angular distributions and excitation functions for the production of these fragments in intermediate energy interactions, we have also attempted to measure the energy spectra of these fragments. Last year, we measured the angular distributions and energy spectra (using differential range techniques) of the light fragments from the interaction of 49 MeV/nucleon ^{12}C with ^{197}Au . The results of this measurement for the ^{24}Na fragments are shown in Fig. 1.

The ^{24}Na angular distribution is strongly forward-peaked similar to previous observations¹ for the reaction of 85 MeV/nucleon ^{12}C with ^{197}Au . The velocity spectrum shows an unusual low velocity component not previously observed.² The peak at ~ 2.3 cm/ns is consistent with the production of ^{24}Na in a binary breakup of Au-like nucleus with the resultant Coulomb repulsion of the two fragments. The low velocity component could be due to multifragmentation of the Au nucleus or some exotic distortion of the fragmenting nucleus.

We were concerned, however, that scattering of beam projectiles from Al target holders, collimators, chamber components, etc. could have caused this low velocity component. Therefore, we attempted to repeat this measurement again in February 1985 at CERN. Unfortunately, due a major accelerator failure prior to our run, the intensity of the 49

Fig. 1. Invariant velocity spectrum and angular distribution of ^{24}Na fragments from 49 MeV/nucleon $^{12}\text{C} + ^{197}\text{Au}$. XBL 8511-4545

MeV/nucleon ^{12}C beams during our run was not sufficient to achieve this goal. We were able, however, to use the 85 MeV/nucleon ^{12}C beam to make a careful measurement of light fragment velocity spectra for the interaction of 85 MeV/nucleon ^{12}C with ^{197}Au . In this measurement the beam was tightly collimated by heavy metal collimators and special care was taken to prevent nuclei scattered from chamber components from reaching our differential range foils. In Fig. 2, we show the measured energy and velocity spectra for ^{46}Sc . While the resolution of the energy measurement is not as good as in the previous measurement, the same essential features appear to be present. A large low velocity component dominates the spectrum with a discernible "normal" component as well.

Analysis of these data should be completed soon.

Footnotes and References

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Light Fragment Excitation Functions

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One of the most interesting aspects of target fragmentation is the reaction producing nuclear fragments that have $A_{\text{fragment}} \leq 1/3 A_{\text{target}}$. At higher projectile energies ($E_{\text{proj}} \leq 2-3$ GeV), such fragments are known¹ to have fragment multiplicities greater than 1 and the process giving rise to these events is called "multi-fragmentation." Excitation functions for the production of these fragments can be parameterized in a simple manner (Fig. 1) and show the threshold for the production of these fragments in light nucleus-heavy nucleus collisions to be $\sim 2-3$ GeV. Firestreak model calculations of the maximum excitation energy of $A=200-240$ nuclei after interaction with 2-3 GeV C ions show $E_{\text{max}} \sim 600-700$ MeV, i.e., about 3 MeV/nucleon, an estimate in agreement with theoretical estimates² of the excitation energy threshold for multifragmentation.

During the past year, we have extended these measurements of light fragment excitation functions into the intermediate energy regime (Fig. 2). We see evidence for a qualitatively different behavior of the light fragment excitation function at these lower energies in nucleus-nucleus collisions, indicative of a different mechanism for the production of light fragments. This finding is consistent with the observation of Lynen, *et al.*⁴ that the production of these fragments in intermediate energy reactions is a

Fig. 2. Energy and invariant velocity spectrum of ^{46}Sc fragments produced in the interaction of 85 MeV/nucleon ^{12}C with ^{197}Au . XBL 8511-4563

binary process rather than a multi-body breakup as observed at higher energies.

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Fig. 1. a) Excitation function for the production of 2 typical light fragments from the interaction of C and Ne with U. b) Same data as (a) replotted to illustrate simple functional form of the excitation function. Data from ref. 3. XBL 8510-4154

Fig. 2. Excitation functions for the production of a typical light fragment ^{28}Mg , in the interaction of ^{12}C and ^1H with ^{197}Au . The $\text{p} + ^{197}\text{Au}$ data is from ref. 5.

XBL 8510-4155

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Ho Target Fragmentation Induced by High Energy ^{12}C , ^{20}Ne and ^{49}Ar

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During the past year we finished the analysis of the measurement of the target fragment isobaric yields in the interaction of relativistic heavy ions with ^{165}Ho . The individual isobaric yield distribu-

tions are shown in Fig. 1, while smooth curves representing each mass yield curve are superimposed in Fig. 2. (In Fig. 2 the curves have been scaled to a constant total reaction cross section using the soft-

Fig. 1. Target fragment isobaric yields in the interaction of relativistic heavy ions with ^{165}Ho . XBL 8511-4546

spheres model.¹⁾ One can see that the isobaric yield curves are identical within experimental error for fragments with $A > 80$, in agreement with limiting fragmentation and factorization. The yields of the lighter fragments do not appear to be factorizable (compare the 1.0 and 0.8 GeV ^{20}Ne and ^{40}Ar induced reactions). This observation has been explained² by arguing that such fragments are produced in small impact parameter, central collisions in which factorization is expected to fail.

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Fig. 2. Superposition of isobaric curves from Fig. 1. Each curve has been multiplied by the ratio $\left(\frac{\sigma_{ss}}{3100}\right)$ where σ_{ss} is the soft spheres total reaction cross section in mb. — 31.2 GeV ^{40}Ar , - - - 21 GeV ^{20}Ne , ···· 8 GeV ^{20}Ne , - · - 3 GeV $^{12}\text{C} + \text{Ho}$.

XBL 8511-4544

Intermediate Energy Heavy Ion Induced Fission of Ho

R. Krauss,* W. Loveland,[†] and G.T. Seaborg

Measurements of the isobaric yield distributions for the interaction of 17–102 MeV/nucleon ^{12}C and ^{16}O with ^{165}Ho were completed. The central fission-like bumps in the yield distributions were integrated to give estimates of the total fission cross section. These data are shown in Fig. 1a.

One observes the fission exit channel to decrease in importance as the projectile energy is raised from 17 to 84 MeV/nucleon. The physics behind this observation is better shown in Fig. 1b in which σ_f/σ_R is plotted as the average angular momentum of the fissioning system, $\langle \ell \rangle$. This latter quantity was estimated using the simple approximate semiclassical relationships:

$E_{\text{proj}} < 10$ MeV/nucleon:

$$\langle \ell \rangle = \frac{2}{3} \left(\frac{\sigma_{\text{fusion}}}{\pi \lambda^2} \right)^{1/2} \quad (1)$$

$E_{\text{proj}} > 10$ MeV/nucleon:

$$\langle \ell \rangle = \ell_{\text{crit}} (P_{\parallel}/P_{\text{CN}}) \quad (2)$$

Fig. 1. a) Fission excitation function from the reaction of ^{12}C and ^{16}O with ^{165}Ho . b) Same data as a) except σ_f/σ_R is now plotted vs. the average angular momentum of the fissioning system. Data from ref. 1 (solid points) and this work (open points).

XBL 8510-4151

Values of ℓ_{crit} and σ_{fusion} were taken from ref. 2, and the fractional transferred linear momentum was cal-

culated using the semiempirical relationship,³

$$(P_w/P_{CN}) = -0.092 \sqrt{\frac{E}{A}} + 1.273 \quad (3)$$

It appears that by organizing the data as a function of the angular momentum of the fissioning system the essential physics is shown, i.e., that of a decreasing angular momentum transfer to the target nucleus as the projectile energy increases from 17 to 84 MeV/nucleon. The singular importance of angular momentum in determining rare earth fissionability can be further demonstrated by remembering that the fission cross section for the interaction of GeV protons (which deposit excitation energies of several hundred MeV) with rare earth nuclei is <10 mb.⁴

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The Momentum Distribution of Projectile Fragments*

R.G. Stokstad

Nuclei that are clearly the remnants of the projectile are observed in all reactions in which the bombarding energy is from a few MeV per nucleon above the barrier to up to 2000 MeV/nucleon. The widths, σ , of the momentum distributions of the fragments change rapidly in the region of bombarding energy from 20 to 100 MeV/nucleon. While it is possible to reproduce the gross behavior of the inclusive widths in the low or in the high energy region with a variety of models, a satisfactory unified description that includes the transition region remains to be developed. The inclusive experimental results that have prompted the statistical model, and its variations are inadequate to distinguish among the different models. At low and intermediate energies, two mechanisms, transfer and sequential decay, are known to contribute. Further study of the reaction mechanism requires exclusive measurements, a number of which are now being made, and many more measurements in the intermediate energy

region. This latter region, which for historical reasons is the last to be explored, is of particular interest and will receive increasing attention in the future. Basic questions, however, remain unanswered.

- 1) Does the reaction mechanism at relativistic energies really sample the Fermi momentum distribution prior to the collision, or are there significant components of thermalization and sequential decay that affect the observed values of σ ?
- 2) What is the bombarding energy dependence for σ for each of the separate mechanisms, transfer and break-up? At present this separation has been made for only one reaction at a few bombarding energies.
- 3) What is the origin of the rapid increase in the reduced width, σ_0 , and how do the different mechanisms sketched in Fig. 1 contribute?

Additional questions undoubtedly will arise as further experiments in the transition region reveal

variations in σ_0 about the gross trend indicated in Fig. 2. Already there are suggestions that there may be significant deviations from an otherwise smooth behavior. Even though it is ten years since the first measurements with high-energy heavy ions, the study of projectile fragmentation is still in its infancy.

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Fig. 1. A schematic illustration of the different processes that may contribute to the formation of projectile-like fragments F, unobserved fragments R, and target-like residues; a) Prompt fragmentation; b) Equilibration of an excited projectile P^* , followed subsequently by particle decay; c) A transfer reaction; d) A transfer reaction that produces an excited fragment F' that equilibrates and subsequently decays by particle emission.

XBL 836-388

Fig. 2. Reduced momentum widths σ_0 obtained in a variety of reactions, as a function of projectile bombarding energy. Data points connected by a vertical line (44,213 and 2100 MeV/nucleon) indicate the range of widths obtained for a set of fragments from a given reaction. The low energy, high energy and transition regions are evident. Although the rapid change in widths in the transition region is clear whether the actual widths σ or the reduced widths σ_0 are considered, the data show less scatter when σ_0 is plotted. The key is as follows:

a) $^{197}\text{Au}(^{20}\text{Ne}, ^{16}\text{O})$	h) $^{12}\text{C}(^{12}\text{C}, ^7\text{Li})$
b) $^{197}\text{Au}(^{20}\text{Ne}, ^{12}\text{C})$	i) $^{12}\text{C}(^{12}\text{C}, ^7\text{Be})$
c) $^{208}\text{Pb}(^{16}\text{O}, ^{12}\text{O})$	j) $^{12}\text{C}(^{12}\text{C}, ^{10}\text{B})$
d) $^{197}\text{Au}(^9\text{Be}, ^7\text{Li})$	k) $^{232}\text{Th}(^{40}\text{Ar}, \text{X})$
e) $^{197}\text{Au}(^9\text{Be}, ^6\text{Li})$	l) $\text{Be} - \text{Pb}(^{16}\text{O}, \text{X})$
f) $^{181}\text{Ta}(^{20}\text{Ne}, \alpha)$	m) $\text{Ni}, \text{Au}(^{40}\text{Ar}, \text{X})$
g) $^{12}\text{C}(^{12}\text{C}, ^6\text{Li})$	n) $^{181}\text{Ta}(^{10}\text{B}, \alpha)$

The dashed line is a calculation based on a peripheral model¹ appropriate for $^{20}\text{Ne}+\text{Au}$, normalized to $\sigma_0=86$ MeV at high energies. XBL 829-9684A

Fragment Excitation in Nucleus-Nucleus Collisions*

B.G. Harvey

The coincidence measurements presented in the preceding report show that the average excitation energy of beam-velocity fragments produced in nucleus-nucleus collisions at 17 MeV/nucleon is about equal to the fragment break-up energy, i.e., about 5–10 MeV. Although there are no direct measurements of fragment excitations at higher projectile energies, there is indirect evidence that they remain remarkably low up to at least 2 GeV/nucleon.

The inclusive cross sections for fragment production are almost the same in the collision of ^{16}O with ^{208}Pb at 20 MeV/nucleon¹ and 2 GeV/nucleon.² For all fragment Z-values from 3 to 7, the ratio of elemental cross sections $\sigma_Z(20 \text{ MeV/nucleon})/\sigma_Z(2 \text{ GeV/nucleon})$ is equal to 1.7 ± 0.4 . This result argues strongly for a similar production mechanism and similar low fragment excitations at both energies.

Fragment cross sections calculated from the abrasion model³ have a much broader mass dispersion for fixed Z than is observed experimentally.⁴ Agreement with experiment is obtained only by assuming that the primary fragments are produced with extremely high excitation energies, as predicted by the abrasion model. The observed fragments are the end products of long evaporation chains. There is, though, no direct experimental evidence for these large excitations.

The surface excitation energy predicted by the abrasion model is much larger when the target is a small nucleus. Table I shows the measured fragment cross sections for $^{40}\text{Ar} + ^{12}\text{C}$ (2.3 MeV/nucleon)⁴ and $^{40}\text{Ar} + ^{58}\text{Ni}$ (44 MeV/nucleon),⁵ as well as the predicted excitation energies. While the excitation energies are very much higher for the ^{12}C target, the inclusive cross sections are remarkably similar. Although it is possible that different primary fragment yields and excitations lead by chance to the same inclusive cross sections, it seems much more likely that the abrasion model predictions of the ex-

Table I.

Comparison of fragment cross sections from $^{40}\text{Ar} + ^{12}\text{C}$ (44 MeV/nucleon) and $^{40}\text{Ar} + ^{58}\text{Ni}$ (213 MeV/nucleon). The last two columns show the abrasion model surface excitation energies for fragments of mass 20, 25 and 30.

Ejectile	σ (mb)		Abrasion Surface Energy (MeV)	
	^{12}C	^{58}Ni	^{12}C	^{58}Ni
^{20}O	0.45	0.71		
^{20}F	16	19	150	34
^{20}Ne	23	30		
^{20}Na	0.3	-		
^{25}Ne	0.10	0.15		
^{25}Na	10	8.6	100	30
^{25}Mg	40	49		
^{25}Al	1.6	5.2		
^{30}Mg	0.12	0.38		
^{30}Al	4.3	2.2	58	23
^{30}Si	50	55		
^{30}P	9	12		

citation energies are quite unreliable. Guerreau *et al.*⁶ also concluded that the excitation energy of fragments from 44 MeV/nucleon $^{40}\text{Ar} + ^{58}\text{Ni}$ or ^{197}Au is quite low.

The model of Friedman⁷ shows that the yield of a fragment depends strongly upon the probability that the observed fragment and the cluster of nucleons removed from the projectile be found at or beyond some critical distance from each other. When this condition is satisfied the cluster can be removed from the projectile by interaction with the target while the fragment can escape without further target interaction. This probability is high when the energy of separation of the projectile into the two parts is small. Good agreement with observed fragment cross sections is obtained without the need to postulate high primary fragment excitations and long

evaporation chains.

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Study of Transfer and Breakup Processes in Reactions of 11 and 17 MeV/nucleon $^{20}\text{Ne} + ^{197}\text{Au}^*$

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R.G. Stokstad, P.J. Countryman,[§] K. Van Bibber,[§] and H. Homeyer**

We have used a 4π charged particle detector, the Plastic Box,¹ to measure the relative importance of transfer and breakup in 11 and 17 MeV/nucleon ^{20}Ne -induced reactions on ^{197}Au targets. Projectile-like fragments were detected and classified according to the number, S , of additional charged particles registered in the plastic scintillator walls. At the lower energy transfer (i.e., $S=0$) is the main contributor to the inclusive ejectile yields. Surprisingly, transfer is still important at the higher bombarding energy. However, breakup is now strong enough to influence the observed distribution of ejectile charge.

The relative amounts of transfer and breakup in inclusive yields were found to be rather insensitive to scattering angle at 341 MeV over the angular range $8-21^\circ$. At both bombarding energies, the inclusive fluorine yields were almost entirely due to charge transfer. The importance of breakup increased with decreasing ejectile charge, leveling off for $Z \leq 7$. In this region of massive charge transfer, pure transfer was responsible for $\approx 60\%$ of the observed inclusive yield at 220 MeV, and $\approx 30\%$ of the yield at 341 MeV.

In order to make comparisons with reaction models we used the experimentally determined breakup cross sections to make reconstructions of the primary ejectile yields. In making these reconstructions, we have employed the following assump-

tions: 1) the breakup is sequential rather than direct, and 2) the sequential decay is dominated by the lowest charged particle thresholds. These assumptions have been borne out by subsequent coincidence experiments in which we identify the charge and angular distribution of the sequentially emitted particles.

The reconstructed primary yields (Fig. 1) are remarkably similar at both bombarding energies. The higher beam energy is seen to enhance the yields of massive charge transfer. It was found that at both 11 and 17 MeV/nucleon, the overlap² and sum-rule³ models were able to reproduce most of the yields. However, for the lightest reconstructed fragment (boron) there were substantial differences, with the sum-rule model more successful at the lower bombarding energy and the overlap model doing better at the higher energy. This is consistent with the physics inherent in each model.

By calculating the fraction of the deduced primary cross section that contributes to the $S=0$ yields, we are able to determine the survival fraction (Fig. 2) of the primary ejectiles, i.e., the probability that the ejectile was produced in a bound state. The results indicate relatively large survival fractions even at 341 MeV, and at both energies the probability of sequential breakup is slowly changing over a large range of transferred mass and, hence, total excitation energy. The large survival fractions (≈ 0.8) at

Fig. 1. The reconstructed primary cross sections are plotted versus primary ejectile charge, as deduced from data at both bombarding energies.

XBL 8412-13511

11 MeV/nucleon indicate that the average excitation energy of the projectile-like fragments is quite low, i.e., well below the threshold for particle emission. At 17 MeV/nucleon, where the survival fractions are ~ 0.3 – 0.6 , the average excitation energy must be about that of the first unbound state. Thus, in the case of a massive transfer, most of the excitation energy must reside in the heavy, target-like fragment. This is consistent with a uni-directional mass flow in these massive transfer reactions.

Footnotes and References

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Fig. 2. The survival fractions are plotted as a function of primary ejectile charge at both bombarding energies.

XBL 8412-13514

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Excitation-energy Sharing and Charge Transfer in 11 MeV/nucleon $^{20}\text{Ne} + ^{197}\text{Au}$

H.R. Schmidt, S.B. Gazes, Y. Chan, R. Kamermans,* and R.G. Stokstad

The sharing of excitation energy in binary heavy ion reactions has been the focus of recent investigations.¹ For intermediate mass projectiles ($A \geq 40$), this sharing was found to depend upon the amount of inelasticity; deep inelastic processes result in thermal equilibrium and hence mass ratio sharing, while quasi elastic processes exhibit an excitation

division that is more nearly equal.

In our recent work² on ^{20}Ne breakup at 11 and 17 MeV/nucleon, we observed relatively large probabilities for producing primary projectile-like fragments in particle-bound states. Such large "survival fractions" imply a low (i.e., ≤ 7 MeV) average excita-

tion energy in the primary ejectiles. We have now performed more detailed studies of ^{20}Ne breakup, and have mapped out the excitations of the primary target-like and projectile-like fragments as a function of the direction and magnitude of the net charge and mass transfer.

We performed experiments using a 220 MeV ^{20}Ne beam on a ^{197}Au target. Projectile-like fragments were detected in a silicon telescope at 28° , near the classical grazing angle. Coincident light charged particles were detected in a large solid angle position sensitive phoswich array.³ The experimental configuration is indicated in Fig. 1(a). The silicon telescope was centered in front of the phoswich array, thus providing almost 4π efficiency for observing alphas and/or protons sequentially emitted by the projectile-like fragments.

Fig. 1(c) shows the x-y distribution of alpha particles in coincidence with ^{16}O fragments (in this case, detected at 16°). There is a depleted region, which is due in part to shadowing by the telescope. The coincident events are then used to calculate a relative velocity between the detected fragments, as illustrated in Fig. 1(b). The resulting v_{rel} plot [Fig. 1(d)] reflects the energy level structure of ^{20}Ne , thus demonstrating the sequential nature of the decay. (In this plot, the telescope shadowing is seen to be small.)

The coincident light particles are predominantly alphas, thus substantiating earlier estimations of the sequential yields based purely on threshold arguments.² In Fig. 2 the E_{rel} spectra for several alpha particle coincident channels are plotted. The abscissa is shifted by the appropriate alpha separation energy. Therefore, assuming (1) sequential decay, and (2) that secondary fragments are left in their ground states, the abscissa represents the excitation energy in the primary projectile-like fragment. Also shown in Fig. 2 is the primary yield that is particle bound, determined by operating the phoswich array in anti-coincidence mode. Since the population distribution of the bound states is not measured, this yield is represented by the area of the hatched region extending up to the alpha emission threshold. For all exit channels shown, the primary fragments are formed

Fig. 1. The experimental setup is illustrated, showing the detection geometry (a) and the sampling of the breakup cone (b). The pattern of detected alphas in the phoswich array is plotted (c), as well as the reconstructed v_{rel} distribution (d). XBL 8510-4348

Fig. 2. The projectile-like fragment excitations are reconstructed for several exit channels. The hatched regions lie below the respective alpha thresholds, and represent the particle-bound yields. The respective neutron and proton thresholds are also indicated.

XBL 8510-4346

predominantly in particle bound states, yielding survival fractions in excess of 90%.

Three body kinematics allow us to calculate the Q values, Q_3 , for the various channels. The results are shown in Fig. 3, with the spectra shifted by the ground state Q values. Again assuming that the two detected fragments are emitted in their ground states, the abscissa of Fig. 3 represents the excitation energy in the target-like fragment following transfer.

The lowest target excitation is obtained for inelastic scattering ($^{20}\text{Ne}, ^{20}\text{Ne}^*$). Slightly higher excitations in the target-like fragment result if one or two neutrons are removed. The capture of a proton by the target ($^{20}\text{Ne}, ^{19}\text{F}^*$) leads to significantly higher excitation than inelastic scattering or neutron removal. Similarly, the capture of two protons produces average excitations about twice as high as the capture of a single proton. The spectra in Fig. 3 correlate much better with charge transfer than with mass transfer; i.e., the spectra for $^{19}\text{F}^*$ and $^{18}\text{F}^*$ are similar. This is also true of the $^{18,17,16}\text{O}^*$ spectra and the $^{22,21,20}\text{Ne}^*$ spectra.

In summary, the division of excitation energy is seen to be strongly correlated with the net charge transfer. The dependence on neutron transfer is less pronounced. Some of this behavior can be understood in terms of the optimum Q -value for transfer reactions.⁴ The reaction mechanism will be studied further by examining data taken at 17 MeV/nucleon, and comparing it to the 11 MeV/nucleon results.

Breakup of $^{16}\text{O}^*$ and $^{17}\text{O}^*$ in the Reaction 27 MeV/nucleon $^{16}\text{O} + ^{197}\text{Au}$

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The projectile breakup mechanism has been extensively studied via heavy ion/alpha coincidence measurements. These studies have been mostly in the energy regime of 10–20 MeV/nucleon bombarding energy. The bulk of the data is consistent with the projectile breakup proceeding via a sequential process. We have examined the $^{16}\text{O} \rightarrow ^{12}\text{C} + \alpha$ channel at 27 MeV/nucleon in order to search for direct breakup, a process which might become more important at near-Fermi velocities.

Fig. 3. The target-like fragment excitations are reconstructed for several exit channels. XBL 8510-4344

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The ECR ion source and 88-Inch Cyclotron provided beams of 424 MeV ^{16}O incident upon a ^{197}Au target. Projectile-like fragments were detected in silicon counter telescopes. Coincident light charged particles were detected in an array of large solid angle position sensitive plastic phoswich detectors, similar to those previously described.¹

The experimentally measured Q_3 spectra are shown in Fig. 1 for $^{12,13}\text{C} + \alpha$ coincidences observed in

The experimentally measured Q_3 spectra are shown in Fig. 1 for $^{12,13}\text{C}+\alpha$ coincidences observed in a close detector geometry. As can be seen in Fig. 1(a) the breakup of $^{16}\text{O}^*$ has a strong quasi elastic component in which the target is left in or near its ground state. In order to investigate the origin of these coincident alphas, the relative energy of the $^{12}\text{C}-\alpha$ system was reconstructed. The resulting spectrum (Fig. 2) shows a strong peak at $E_{\text{rel}}=4.4$ MeV which, if associated with a sequential projectile decay, would correspond to 11.5 MeV of excitation. This is consistent with the findings of Rae *et al.*² at 9 MeV/nucleon, in which the 11.47 MeV state in ^{16}O is strongly populated. Further evidence for a sequential mechanism at 27 MeV/nucleon is the sharp drop in breakup yield for $E_{\text{rel}} < 2.6$ MeV. This low energy region can be reached only by direct breakup, since it lies below the first particle decaying state of ^{16}O . While such a "forbidden" region was strongly populated by $\alpha+t$ coincidences in the ^7Li -induced reactions studied by Shotter *et al.*,³ the ^{16}O data are dominated by the sequential structure above 2.6 MeV.

In addition to the Q_{ggg} peak observed in the $^{12}\text{C}+\alpha$ Q -value spectrum, there is a very prominent inelastic bump centered at ~ 34 MeV which indicates the presence of another mechanism. The most likely interpretation is a pickup-breakup (or "transfer-reemission") process, in which $^{17}\text{O}^*$ is formed via neutron pickup, followed by neutron and alpha emissions. The neutron is unobserved in the present experiment. Kinematics for such a four body final state predict that it would produce a broad peak centered at ~ 33 MeV, in excellent agreement with the data. Such a process also explains the presence of a similar structure in $^{15}\text{N}+p$ coincidences, as well as the absence of an inelastic bump in the $^{13}\text{C}+\alpha$ coincidence data [Fig. 1(b)]. Finally, the presence of an inelastic bump has been seen in $(^{16}\text{O}, ^{16}\text{O}')$ reactions at 25 MeV/nucleon⁴ and was ascribed to "contamination" by $^{17}\text{O}^*$ decay. The present work indicates that neutron pickup and inelastic scattering to unbound states in the respective projectile-like fragments are competitive processes in 27 MeV/nucleon $^{20}\text{Ne}+^{197}\text{Au}$ reactions.

Fig. 1. The Q_3 spectra are shown for (a) $^{12}\text{C}+\alpha$ and (b) $^{13}\text{C}+\alpha$ coincidences. The ejectile is detected at $\theta=9^\circ$ and the alpha particle at $\theta=9^\circ$, $\phi=0 \pm 15^\circ$. Q_3 is defined by $Q_3=(E_1+E_2+E_3)-E_{\text{proj}}$, where E_{proj} is the kinetic energy of the beam and $E_{1,2,3}$ are the kinetic energies of the three bodies in the final state. Q_{ggg} is the value of Q_3 when all three bodies are in their ground states. XBL 8510-11921

Fig. 2. The $^{12}\text{C} + \alpha$ coincidences are plotted versus the relative energy of the detected fragments. XBL 8510-11920

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Projectile Breakup and Transfer-Reemission Reactions in the $^{12}\text{C} + ^{20}\text{Ne}$ System

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Heavy-ion reactions with three charged particles in the final state have been of considerable interest in recent years. In the present study we investigated these reactions in the $^{12}\text{C} + ^{20}\text{Ne}$ system by bombarding a ^{12}C target with a 158 MeV beam of ^{20}Ne , i.e., by using "reverse kinematics." In such a relatively light system it is possible to identify discrete intermediate states not only in the sequential decay of the projectile, but also in the sequential decay of fragments formed through the transfer of nucleons from the projectile to the target or vice versa. The latter process, which we call a transfer-reemission reaction, has not been extensively investigated so far, although it is especially interesting because it may selectively lead to high spin states of specific cluster structure, particularly if the transferred nucleons constitute an alpha particle.

In our study, charged particles were detected and identified with telescopes consisting of position sensitive ΔE and E silicon detectors.¹ Two-dimensional information on the position was obtained for each telescope. We concentrated our measurements on the $^{12}\text{C}(^{20}\text{Ne}, \alpha ^{16}\text{O})^{12}\text{C}$ and $^{12}\text{C}(^{20}\text{Ne}, \alpha ^{20}\text{Ne})^8\text{Be}$ reactions. The α - ^{16}O and α - ^{20}Ne coincidences were analyzed event by event with full reconstruction of momenta and kinetic energies in each 3-body event. Hence the total kinetic energy $E_{\text{tot}} = E_1 + E_2 + E_3$ and the relative energies in the corresponding sub-systems, $E_{\text{rel}}(1,2)$ and $E_{\text{rel}}(1,3)$, could be calculated. (Here the index "1" denotes the α -particle, "2" denotes the detected heavy ion, and

"3" refers to the unobserved third particle.)

In the $^{12}\text{C}(^{20}\text{Ne}, \alpha ^{16}\text{O})^{12}\text{C}$ reaction the spectrum of E_{tot} has a strong peak corresponding to the three final particles in their ground states ($Q_{\text{ggg}} = -4.73$ MeV). The analyses presented in Figs. 1 and 2 are limited to this ground state peak.

Fig. 1 shows the distribution of the coincidence events for the reaction $^{12}\text{C}(^{20}\text{Ne}, \alpha ^{16}\text{O}_{\text{g.s.}})^{12}\text{C}_{\text{g.s.}}$ with the telescopes placed at $\langle \theta_1 \rangle = 26^\circ$ and $\langle \theta_2 \rangle = 10^\circ$, plotted as a function of the relative energies $E_{\text{rel}}(1,2)$ and $E_{\text{rel}}(1,3)$. For this angular configuration one sees intermediate states only in $E_{\text{rel}}(1,2)$, i.e., in the $\alpha + ^{16}\text{O}$ sub-system. This means that the sequential breakup $^{12}\text{C}(^{20}\text{Ne}, ^{20}\text{Ne}^* \rightarrow \alpha + ^{16}\text{O}_{\text{g.s.}})^{12}\text{C}_{\text{g.s.}}$ dominates in the class of collisions that can be observed at these detector angles. The observed 2-body intermediate states can be easily identified as the known excited states in ^{20}Ne (see top of Fig. 1).

Fig. 2 shows a similar analysis for a wider angular configuration ($\langle \theta_1 \rangle = 26^\circ$, $\langle \theta_2 \rangle = -10^\circ$) which is sensitive to higher relative kinetic energies in the $\alpha + ^{16}\text{O}$ sub-system. There is one strong line at $E_{\text{rel}}(1,2) = 8.2$ MeV that can be identified with the 13.01 MeV (4^+), 13.05 MeV (4^+) doublet in ^{20}Ne . It is very interesting that, in addition to the intermediate states in ^{20}Ne , one can clearly see an intermediate state in the $\alpha + ^{12}\text{C}$ sub-system, at $E_{\text{rel}}(1,3) = 13.6$ MeV that corresponds to an excitation energy of 20.8 MeV in ^{16}O . This intermediate state is populated in

Fig. 1. Scatter plot for the analysis of 2-body intermediate states in the reaction with three particles in the final state. Intermediate states only in $E_{\text{rel}}(1,2)$ are seen. They correspond to sequential breakup of the projectile. XBL 8510-11922

the transfer-reemission reaction

and can be identified with the known 7^- (20.9 MeV) state which has also been populated very selectively in the transfer-reemission reaction induced by ^6Li projectiles.²

We also observed another example of the transfer-reemission process, namely, the pickup of an α -particle by the projectile to form ^{24}Mg in the reaction $^{12}\text{C}(^{20}\text{Ne}, ^{24}\text{Mg}^* \rightarrow \alpha + ^{20}\text{Ne}_{\text{g.s.}})^{12}\text{C}_{\text{g.s.}}$. A state (or a group of states) at $E_{\text{exc}}(^{24}\text{Mg}) = 16.5$ MeV was selectively excited at the angular configuration $\langle \theta_1 \rangle = 26^\circ$, $\langle \theta_2 \rangle = -10^\circ$.

^{12}C Decay of ^{24}Mg Following Nuclear Inelastic Scattering

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Both the electro-fission of ^{24}Mg and the formation of ^{24}Mg via the radiative capture reaction, $^{12}\text{C}(^{12}\text{C}, \gamma_0)^{24}\text{Mg}_{\text{g.s.}}$, have been observed.¹⁻³ Concerning nuclear interactions, only statistical decay of

Fig. 2. Same as Fig. 1, except $\langle \theta_1 \rangle = 26^\circ$, $\langle \theta_2 \rangle = -10^\circ$. Intermediate states in both $E_{\text{rel}}(1,2)$ and $E_{\text{rel}}(1,3)$ are seen. They correspond to projectile breakup and transfer-reemission reactions, respectively. XBL 8510-11923

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^{24}Mg into $^{12}\text{C} + ^{12}\text{C}$ following the compound nucleus reaction $^{12}\text{C}(^{16}\text{O}, \alpha)^{24}\text{Mg}^*$ has been reported.⁴ An attempt to observe the ^{12}C decay of ^{24}Mg in the inelastic scattering reaction $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C}$ was not

conclusive with respect to whether the observed effect was statistical or partly non-statistical.⁵ In the present work we took advantage of the newly developed $^{24}\text{Mg}^{8+}$ beam from the ECR source installed at the LBL 88-Inch Cyclotron to further investigate the decay of a ^{24}Mg following the nuclear inelastic scattering--by using a "reverse kinematics" reaction $^{24}\text{Mg} + ^{12}\text{C}$.

With ^{24}Mg as a beam and a light target such as ^{12}C , the inelastically scattered ^{24}Mg nuclei move forward with almost the beam velocity, and therefore their decay products have sufficiently high energies to be detected and identified. Moreover, in this use of "reverse kinematics," all the decay products from the projectile are emitted within a narrow breakup cone that makes their detection highly efficient.

A 0.5 mg/cm^2 ^{12}C target was bombarded with 357 MeV ^{24}Mg projectiles. Reaction products were detected in two large-solid-angle telescopes (5 msr each) consisting of $40 \text{ } \mu\text{m}$ ΔE detectors and position sensitive E detectors. The telescopes were placed at $+10^\circ$ and -10° with respect to the beam. They allowed detection of two particles with opening angles ranging from 15° to 25° .

We selected coincidences of two ^{12}C nuclei by determining both the charge and mass of each nucleus. From precise simultaneous measurements of their energies ($\delta E/E = 0.4\%$) and emission angles ($\delta\theta = 0.15^\circ$), the momentum and hence the energy of the third ^{12}C could be calculated. The spectrum of the total kinetic energy, $E_{\text{tot}} = E_1 + E_2 + E_3$, is shown in Fig. 1. One can clearly see the peak corresponding to the formation of three ^{12}C nuclei in their ground states ($Q_{\text{ggg}} = -13.93 \text{ MeV}$). The two other peaks at lower E_{tot} energies correspond, respectively, to one and two of the three ^{12}C nuclei being in the first excited state (4.44 MeV).

Events in the ground state peak at Q_{ggg} may be interpreted as resulting from sequential breakup of ^{24}Mg following inelastic scattering: $^{12}\text{C}(^{24}\text{Mg}, ^{24}\text{Mg}^*) \rightarrow ^{12}\text{C}_{\text{g.s.}} ^{12}\text{C}_{\text{g.s.}}$. Information on the excited states in ^{24}Mg which decay into $^{12}\text{C} + ^{12}\text{C}$ can be obtained from the spectrum of the relative energy E_{rel} of the two detected ^{12}C nuclei. The spectrum of the excitation energy in ^{24}Mg , $E_{\text{exc}} = E_{\text{rel}} + 13.93$

Fig. 1. Spectra of the total kinetic energy $E_{\text{tot}} = E_1 + E_2 + E_3$ in the $^{12}\text{C}(^{24}\text{Mg}, ^{12}\text{C} ^{12}\text{C})^{12}\text{C}$ reaction at $E_{\text{lab}} = 357 \text{ MeV}$.
XBL 8510-11924

MeV, is presented in Fig. 2. With an accuracy of about 0.2° in the measurements of the relative angle between the two ^{12}C 's, the energy resolution in this spectrum is about 400 keV. The spectrum in Fig. 2 shows a pronounced structure with peaks at $E_{\text{exc}} = 22.1 \text{ MeV}$, 23.7 MeV and 24.8 MeV . The first peak coincides with the 2^+ resonance at $E_{\text{exc}} = 22.0 \text{ MeV}$ observed³ in the radiative capture reaction $^{12}\text{C}(^{12}\text{C}, \gamma_0)^{24}\text{Mg}_{\text{g.s.}}$. The other distinct peak at $E_{\text{exc}} = 24.8 \text{ MeV}$ was not seen either in the radiative capture or in electro-fission reactions. This may indicate that its multipolarity is $J^\pi = 4^+$ or higher, and consequently not populated in the electromagnetic reactions.

The structure seen in Fig. 2 cannot be explained on purely statistical grounds because the width of statistical fluctuations in this region of excitation energies in ^{24}Mg (about 100 keV) is much smaller than that observed in our experiment. Therefore one can conclude that the structure seen in Fig. 2 reflects the presence of states or groups of states that selectively decay into $^{12}\text{C} + ^{12}\text{C}$ with significantly higher probability than other states in this region of excitation energies. It seems that these particular states with the large ^{12}C decay width must

have a well developed molecular structure.

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Fig. 2. Spectra of excitation energy in ^{24}Mg , obtained from the measured relative energy E_{rel} gated by the ground state peak in E_{tot} at $Q = Q_{\text{ggg}}$.

XBL 8510-11925

Surface Desorption Induced by High Charge State Ions

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An ion incident upon a surface can cause atoms of the surface to be ejected. This process, called desorption or sputtering, may occur for incident atoms having energies varying from a threshold value of the order of tens of electron volts to cosmic ray energies. The mechanisms through which surface atoms are ejected can in principle depend on the ion's mass, energy and charge state and, of course, on the nature of the surface. Not much is known about the dependence on charge states exceeding one or two times ionized, although there is some evidence for the sputter yield from an insulator to depend on the charge state of a high energy heavy ion.¹ Insulators might be expected to show such an effect because local ionization induced by the passage of the ion may persist long enough for a "Coulomb

explosion" to eject surface atoms. Part of the interest in studying sputtering with very highly charged ions at low energies is that the ionization energy of the incident atom can be comparable to its kinetic energy, and this, under the right circumstances, could have significant consequences for the desorption process. The aim of the present research is to study both the total sputtering yield and the angular distribution of sputtered particles for a wide range of charge states of low energy ions, for several different types of target materials. This program takes advantage of the high charge state ions from the new electron cyclotron resonance source (ECR) at the 88-Inch Cyclotron.

One preliminary experiment has been carried out to date, wherein a gold foil was bombarded with

argon ions of different charge states. A metal target was chosen for the first experiment for several reasons. First, a conductor is convenient in that it does not become charged by the ion beam. Second, there is an abundance of low energy sputtering data for singly charged ions on metals. Third, theoretical models have been quite successful in describing low energy sputtering of metals. The most prevalent theory, developed by Sigmund, includes no explicit dependence on the charge state of the ion,² so that one might predict, to lowest order, that the sputtering yields should be the same for a metal.

The experimental configuration is shown in Fig. 1. Primary beams of 60 keV $^{40}\text{Ar}^{4+}$, $^{40}\text{Ar}^{8+}$, and $^{40}\text{Ar}^{11+}$, were generated by ECR source. The ion beam was directed into a chamber that, during the runs, was at $\sim 3 \times 10^{-8}$ torr. The primary beam was incident along the target normal, and the sputtered atoms were collected on high purity aluminum foils mounted on a cylindrical holder. The catcher foils and collimators were biased relative to the target to suppress secondary electron emission.

After the bombardments, the density of sputtered atoms on the catcher foils was determined from Rutherford backscattering using a 6 MeV $^{16}\text{O}^{2+}$ beam generated by the Caltech Van de Graaf accelerator.

The results are presented in Fig. 2. The sputtering distributions were all fit by a function of the form $A \cos^b \theta$, where b is ~ 2 .

The total yields S are given in Table I. The measured sputter yields increase from 7.6 to 9.2 as the charge state varies from 4^+ to 11^+ . The error of ± 1.2 on each value includes systematic as well as random errors. Some of the systematic errors cancel in the ratio of two yields: the ratio for $S(11^+)/S(4^+)$ is 1.2 ± 0.1 . Thus there is some evidence (at the 2σ level) for an increase in sputter yield with charge state. The yield for $\text{Ar}^{(1)+}$ measured³ at 60 keV is 9 ± 4 . Further experiments will be conducted over a wider range of charge states in order to verify the charge-state dependence for Ar on Au suggested by the above results. Measurements on semiconductors and insulators are planned.

Fig. 1. Experimental configuration used for sputtering. The primary beam was normally incident on the target. Sputtered material was collected on cylindrical aluminum catcher foils. Collimators and collector foils were biased as shown to suppress secondary electron emission. XBL 8510-9585

Fig. 2. Areal densities of gold on catcher foils as a function of angle θ from target normal. All densities are normalized to $^{40}\text{Ar}^{8+}$ run. Uncertainty of angle from target normal is less than $\pm 4^\circ$ in all cases. Uncertainty of the areal densities is $\pm 15\%$.

XBL 8510-4336

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Table I. Total sputtering yields for different charge states of argon incident on gold. These were calculated by fitting the sputtering distributions with a function of the form $A \cos^b \theta$ integrating this function over 2π steradians to obtain the total number of sputtered particles, and normalizing to the number of incident ions.

Incident Ion	b	Total Sputtering Yield
$^{40}\text{Ar}^{4+}$	2.5	7.6 ± 1.2
$^{40}\text{Ar}^{8+}$	2.3	8.4 ± 1.2
$^{40}\text{Ar}^{11+}$	2.2	9.2 ± 1.2

The Dependence of Heavy Ion Induced Adhesion on Energy Loss and Time*

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The adhesion of thin metallic films to substrates can be improved by the passage of ionizing radiation through the interface. The resulting adhesion can be quite strong, even for insulating substrates such as polymers and oxides. High velocity, heavily ionizing charged particles such as fluorine and chlorine have been shown to be particularly effective in enhancing adhesion.¹

The threshold dose D^{th} (ions/cm²) required for a thin film to adhere to its substrate rather than to a strip of Scotch tape peeled at 90° is a frequently used indicator of an ion's effectiveness in enhancing adhesion.² The variation of D^{th} with projectile species correlates well with the stopping power dE/dx (MeV mg⁻¹cm²), which is the average energy lost per unit distance of the projectile in the film. A previous measurement of this correlation for a range of projectiles varying from helium to holmium ($Z = 67$) showed that $D^{\text{th}} = 4 \times 10^{14} (dE/dx)^{-1.6 \pm 0.2}$ for a film of 500 Å of gold thermally deposited on a tantalum substrate.^{3,4}

We have recently completed a systematic study of adhesion enhancement induced by different heavy ion projectiles bombarding thin (500 Å) films of gold

on substrates of tantalum and silicon (both having native oxides). Two of the observations made in this work appear to be of particular significance and are reported here.

The substrates of cold-formed tantalum sheet were cleaned in hot detergent, rinsed in de-ionized water, etched in a 1:1 solution of nitric acid and water, and rinsed again in water. A rinse in ethanol preceded loading the samples into the evaporator. Before depositing the gold at a pressure of $\approx 8 \times 10^{-6}$ Torr, the samples were subjected to a glow discharge cleaning. An Auger analysis indicated that the actual substrate onto which the gold was deposited was a native tantalum oxide of about 40 Å thickness.

The samples were irradiated by beams of ^{12}C , ^{16}O , ^{28}Si , ^{35}Cl and ^{58}Ni at 2.85 MeV/nucleon from the Pelletron accelerator of the Weizmann Institute. Our results are shown in Fig. 1 and may be expressed by $D^{\text{th}} = 10^{17} (dE/dx)^{-3.0 \pm 0.2}$ and $D^{\text{th}} = 6 \times 10^{18} (dE/dx)^{4.1 \pm 0.3} \text{ cm}^{-2}$ for tantalum and silicon, respectively. While our results also are well described by a power law, the values of the exponents are quite different for silicon and tantalum

substrates, and the exponent for the Au-Ta system is different from that reported in refs. 3 and 4. We suspect that the different results arise from the preparation of the surface of the sample, and could depend on the level of other elements such as hydrogen or oxygen (or their compounds) adsorbed on the surface of the substrate. While this inference is speculative, it is clear from Fig. 1 that the relative effectiveness of different ions in producing adhesion is quite sensitive to the particular interface.

The second observation we report concerns the time dependence of the adhesion enhancement. By repeating the peel test over a period of time on samples irradiated with different doses, we found that the level of adhesion decreased with time (a point of concern for practical applications). Fig. 2 shows the dose required to pass a peel test performed a given number of days after the bombardment. We found that the rate of decrease in adhesion was more rapid the thinner the Au film, and that the level of adhesion could be restored by a subsequent bombardment. The Au-Si system also showed a time dependence, although not as pronounced as for Au-Ta.

The time dependence of the adhesion enhancement is not likely to arise from an intrinsic time dependence of the induced adhesive bond (e.g., a meta-stable bond) since it depends on the thickness of the Au film and otherwise resembles a diffusion-driven process. (The dashed line is of the form $D^{\text{th}} = a + b \sqrt{t}$ where a and b are adjusted constants and t is the time after bombardment.) It appears likely that ambient gases such as oxygen or water vapor may diffuse to the interface and thereby weaken the bonds induced as a result of bombardment. Thus, the presence or subsequent introduction of relatively small numbers of extraneous atoms at the interface may provide the explanation both for the large variation in the power law dependence observed here and in ref. 4, for Au-Ta, and for the observed time dependence.

Fig. 1. The threshold dose for the Scotch-tape test for different bombarding ions (at normal incidence) for a 500 Å gold film on a tantalum oxide substrate and for a 250 Å gold film on a silicon (plus native oxide) substrate. In order of increasing dE/dx values,⁵ the open squares correspond to beams of ^{12}C , ^{16}O , ^{28}Si , ^{35}Cl and ^{58}Ni , all at 2.85 MeV/nucleon. Note the difference in both magnitude and slope of the results obtained here and in ref. 4 for Au-Ta systems. The straight lines correspond to $(dE/dx)^{-1.6}$ (the dashed line), $(dE/dx)^{-3.0}$ for Au-Ta and $(dE/dx)^{-4.1}$ for Au-Si (solid lines). XBL 855-9978

Fig. 2. The threshold dose required for an irradiated spot on a 600 Å Au-Ta sample to pass the Scotch-tape test if the test is applied a period of time after the bombardment. The increased dose required as a function of time after the bombardment corresponds to a loss of adhesion with time. XBL 855-9975

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Characterization of Hot Compound Nuclei from Binary Decay into Complex Fragments*

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In heavy systems which subsequently undergo fission very large energy depositions have been inferred from linear momentum transfer data. Similarly, in lighter systems a component of the resulting distribution of reaction products has been interpreted as arising from the ordinary evaporation of a very hot compound nucleus. A more general approach is based upon the recently characterized compound nucleus emission of complex particles combined with a reverse kinematics reaction,^{1,2} which permits both a verification of compound nucleus decay and the determination of the momentum transfer.

In a series of low energy experiments^{1,3,4} where complex fragment emission was studied as a function of mass and excitation energy (50–140 MeV), it was concluded that in the energy range explored these processes could be unequivocally and completely characterized as due to compound nucleus decay. If these intermediate mass fragments do indeed arise from compound nucleus emission even at intermediate energies, they are ideally suited to investigate compound nucleus decay over the broadest range of masses and excitation energies.

In this work we have obtained conclusive evidence that the reactions of 25 and 30 MeV/nucleon $^{93}\text{Nb} + ^9\text{Be}$, ^{27}Al give rise to a thermalized intermedi-

ate formed with a very large momentum transfer and energy deposition as high as 400 MeV, which then undergoes a compound nucleus binary decay producing fragments of intermediate mass and charge. Although the term compound nucleus is usually employed for complete fusion reactions, we will use the same term to also refer to the equilibrated product produced in an incomplete fusion reaction.

The experiments have been carried out at the Bevalac. Beams of 107 particles/pulse of ^{93}Nb with energies of 25 and 30 MeV/nucleon impinged on targets of ^9Be (2.3 mg/cm²) or ^{27}Al (3.0 mg/cm²). Two large acceptance angle $\Delta E(\text{gas})$, $E(\text{Si})$ telescopes were placed on either side of the beam at angles of 5.5° and -11°, respectively.

The singles invariant cross sections plotted in the velocity-Z plane are shown in Fig. 1 for the two targets and the two bombarding energies. For all systems, the charge distributions consist of three components: a) a prominent hill, beginning near the projectile Z value (41) and extending toward smaller atomic numbers; b) two distinct ridges at intermediate atomic numbers whose separation in velocity increases with decreasing atomic number; and c) a low velocity hill near the target Z value.

Fig. 1. Singles distribution of reaction products plotted as logarithmic contours of invariant cross section $\{(1/V^2) (\delta^2\sigma/\delta\Omega\delta V)\}$ in the Z -velocity plane for the 5.5° telescope. The arrows indicate the velocities for 1) full momentum transfer 2) the experimentally determined momentum transfer and 3) the beam. Calculated (dashed lines) average velocities of complex fragments for the maximum and minimum angles of the telescope (3° and 8°) are indicated.

XBL 859-8978

The first and strongest component consists of a large number of events near the projectile Z value and is visible only at small angles in the most forward telescope. This component is consistent with the tail end of the evaporation residue distribution from a highly excited compound nucleus.

The third component, visible at small Z values and low velocities, is apparently related to the target. The second component consists of fragments of intermediate Z value, which present two well separated velocity components of nearly equal intensity. The presence of two velocity components is practically by itself spectacular evidence for the binary decay of a compound nucleus system. In fact the splitting into two components arises from forward and backward emission of fragments with Coulomb-like energies in

the center of mass. From the average velocity of the two components, one can derive the mean source velocity for each reaction system. These are indicated by the arrows labeled 2 in Fig. 1. For comparison, the recoil velocity for complete fusion (v_{cf}) and the beam velocity are indicated by the arrows labeled 1 and 3, respectively.

From the above data it appears that a very large transfer of mass and energy leads to the formation of an object that relaxes into a hot compound nucleus. Such a fast moving compound nucleus in turn emits fragments in binary decay with Coulomb-like energies, thus leading to the appearance of the double velocity solution for intermediate Z values. The velocities of the two components can be evaluated theoretically by assuming that the fragments possess Coulomb energies and by correcting the final charge of the observed fragment for sequential decay. The dashed lines shown in Fig. 1 for all reactions correspond to calculations for the extreme acceptance angles of the telescopes and are in good agreement with the data.

The binary nature of the intermediate mass fragment production process is confirmed by the coincidence data shown in Fig. 2, where the sum $\langle Z_1 + Z_2 \rangle$ is presented as a function of Z_2 . The dashed lines are estimates of the mean compound nucleus charge transfer. The measured total charge is smaller due to light particle evaporation from the excited primary products and/or the initial system. For the ${}^9\text{Be}$ target, the average charge loss is 2–4 Z units, while for the ${}^{27}\text{Al}$ target, it is 13–15 Z units, reflecting the differing amounts of excitation energy with which the compound nuclei are formed. In the same figure, calculations (solid lines) from the evaporation code PACE⁵ are presented.

The results from our measurement imply the formation of a compound nucleus in an incomplete fusion process with momentum transfer consistent with the Viola systematics and an excitation energy corresponding to the associated mass transfer. The excitation energies range from 150 to 400 MeV (up to 4 MeV/nucleon) with corresponding temperatures of 4.0 and 6.4 MeV, respectively. Throughout this range of excitation energies, complex particle emis-

sion occurs consistently and abundantly as an important decay process, easily identifiable because of its binary nature and very useful for the determination of momentum and energy transfer. It appears that despite temperatures comparable with the nuclear binding energy and energies per nucleon approaching the same, the system still manages to fuse, relax and decay as a compound nucleus. Thus it appears that multifragmentation does not yet play a major role for these systems at these bombarding energies.

Footnotes and References

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Fig. 2. The mean sum, $\langle Z_1 + Z_2 \rangle$ of coincidence events (solid symbols) plotted as a function of Z_2 . The dashed lines indicate the average charge of the compound system as estimated from the mass transfer. The charge loss for binary events due to sequential evaporation was estimated using the PACE⁵ code and the residual $Z_1 + Z_2$ values are indicated by the solid curves.

XBL 859-8977

Evidence For Very Asymmetric Fission of ^{244}Cm

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The emission of large fragments, intermediate in mass between alpha particles and symmetric fission fragments, has been used in recent studies to determine the conditional saddle point masses, or barriers, as a function of asymmetry.¹⁻³ We have thus confirmed the Businaro-Gallone transition³ and verified the importance of a finite range correction to the liquid drop model.^{2,4} In earlier work we studied the decay of intermediate mass compound nuclei ($A \sim 110$). As the asymmetry of the exit channel is increased, our earlier data and liquid-drop model cal-

culations show a gradual decrease in yield followed by a rapid increase for light fragments with $Z < 6$.

In order to extend our studies of large fragment emission to the decay of very heavy compound nuclei, we studied the compound nucleus decay of ^{244}Cm . The existence of an enhanced very asymmetric mode of fission in heavy nuclei is expected both on the basis of the liquid drop model and from effects due to the $Z=8$ and $Z=82$ shell closures. Earlier radiochemical work⁵ identified a very asymmetric mode of fission of ^{241}Pu at 39.5 MeV of exci-

tation, which was believed to be associated with ternary fission (Fig. 1). Indeed, there is no real evidence that the very light products are due to division into three fragments, since only inclusive cross sections were measured in the radiochemical work.

In order to investigate the origin of these very light products, we have studied the decay of $^{244}\text{Cm}^*$ compound nuclei at 70 MeV of excitation produced in bombardment of ^{12}C with 8.4 MeV/nucleon ^{232}Th beams from the SuperHILAC. The reverse kinematics of this reaction make possible the detection of both fragments in kinematic coincidence, which uniquely identifies the binary events with large detection efficiency.

The light fission fragments were detected with an X-Y position sensitive gas ΔE , Si(Li) E telescope spanning 20° – 29° in the laboratory. The heavy fission fragments were detected in an X-Y position sensitive multiwire avalanche counter covering an angular range of 3° – 17° . Individual Z identification up to Z=45 was achieved. The binary events were unambiguously identified by an event-by-event kinematic reconstruction as follows. The measured Z_3 , E_3 , θ_3 , ϕ_3 for each fragment were used to obtain the secondary mass A_3 assuming charge equilibration. The observed energy was corrected event by event for energy loss in the absorber, the window and the target, and then a correction for neutron evaporation was applied, assuming that the total kinetic energy loss is divided between the fragments according to the masses and that about 12 MeV of total kinetic energy loss is required on the average per emitted neutron. In this way the quantities Z_3 , A_3 , E_3 , θ_3 , ϕ_3 for each primary fragment were obtained. These were used to calculate the expected angles θ_4 and ϕ_4 for the heavy recoils assuming binary kinematics. In turn from these the quantities $\Delta\theta_4 = \theta_4(\text{obs}) - \theta_4$ and $\Delta\phi_4 = \phi_4(\text{obs}) - \phi_4$ were calculated for each event. A correlation plot of $\Delta\theta_4$ vs $\Delta\phi_4$ for the binary events should clustering around 0° in both directions. Such a plot is shown in Fig. 2 for detected light fragments with Z=26. The events clustering within the limits of the kinematic reconstruction, including possible fluctuations due to neutron

Fission in Which Three Fragments Are Produced

Fig. 1. Fission mass yield distribution of ^{238}U excited by 30.6 MeV ^3He ions. The dashed line gives the expected mass yield from reflection of the light mass yield assuming binary events (from ref. 5).

XBL 5812-4893

Fig. 2. Correlation map of the $\Delta\theta_4^0$ vs. $\Delta\phi_4^0$ difference angles showing the clustering of the binary events in the indicated mask from the $^{232}\text{Th} + ^{12}\text{C}$ experiment for Z=26.

XBL 8512-4894

or light charged particle emission from the lightest Z_3 fragments, were identified with the binary events. The relative yields of the binary products as a function of Z are shown in Fig. 3. The cluster of binary products observed around $Z=10$ is identified with a very asymmetric mode of fission. The yields of the asymmetric component is consistent with earlier excitation functions, suggesting that the bulk of the radiochemically observed very asymmetric component is probably due to binary fission.

Further analysis is in progress to obtain the absolute cross sections for these products from analysis of the center of mass angular distributions. We plan to pursue liquid drop model calculations to see whether these results can be understood more quantitatively.

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Fig. 3. Relative yield of the binary events as function of the detected Z for the light fragment. The cluster of a events around $Z \approx 10$ is due to the very asymmetric fission of ^{244}Cm . XBL 8512-4895

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Excitation Energy Division in the First 160 MeV of Total Kinetic Energy Loss for the Reaction 684 MeV $^{80}\text{Kr} + ^{174}\text{Yb}$

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A fundamental observable for determining the mechanism for energy damping in heavy ion reactions is the division of excitation energy between the two exit channel fragments. If particle exchange is the primary means of energy dissipation, then the excitation energy should be divided approximately

equally. However, as the interaction time increases the division of excitation energy should evolve toward the equilibrium limit. This limit predicts a division of excitation energy in proportion to the fragment masses. The evolution of the excitation energy division with the reaction time has been treated

theoretically by Moretto¹ and Randrup.² In both cases it is found that the excitation energy divides nearly equally for short interaction times or small total kinetic energy losses (TKEL) and then, as the interaction time increases, the division of excitation energy becomes skewed in favor of the heavy fragment.

The question of the excitation energy division as a function of TKEL can be addressed by determining the number of neutrons evaporated from the heavy fragment as function of the TKEL. Since the number of evaporated neutrons is a good measure of the fragment's excitation energy, we determined both the total excitation energy (from the TKEL) and the excitation energy of one fragment.

The system studied was 684 MeV $^{80}\text{Kr} + ^{174}\text{Yb}$. The charge, energy and position of the projectile-like fragment was determined by its detection in a position sensitive ionization chamber (IC). The position of the target-like fragment was determined by detecting this fragment in a position sensitive parallel plate avalanche counter (PPAC). This information determines the two body kinematics and therefore allows for the calculation of the TKEL. In addition to the particle detectors described above, 6 Compton-suppressed intrinsic Ge detectors were used to detect coincident gamma rays. The isotope distribution of the target-like fragment residue, as determined by the intensities of yrast transitions, was extracted as a function of TKEL and charge asymmetry. Assuming that the relationship between the charge split and the mass split in the reaction is independent of TKEL, the final isotope distribution is a direct measure of the energy spent in the evaporation process.

Fig. 1 shows the mean mass of Hf isotopes for different TKEL bins plotted against a calculated excitation energy of the heavy fragment. This excitation energy is calculated by scaling the mean TKEL for each bin by the ratios suggested by the concepts of particle transfer and thermal equilibrium. The solid lines are evaporation calculations with extreme assumptions concerning the angular momentum. Comparison of the scaled data and the calculations indicates that the excitation energy is divided roughly equally for the first 150 MeV of TKEL. This con-

Fig. 1. The mean mass of Hf isotopes for various bins in TKEL as a function of a calculated excitation energy of the target-like fragment. The mean mass is determined by the relative intensities of the $4^+ \rightarrow 2^+$ transitions. These data have been selected by requiring $Z_3=34$. The solid lines are evaporation calculations assuming initial angular momenta of $14=20\hbar$ (upper line) and $14=50\hbar$ (lower line).

XBL 8512-9037

clusion is similar to that reached by studying the fission mass asymmetry of heavy target-like fragments.³

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The Second Rise of the Spin Alignment in Heavy Ion Reactions

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The transfer of angular momentum from orbital to intrinsic degrees of freedom in heavy ion collisions has been studied by means of a variety of techniques. Some of the most informative investigations of this process have measured the alignment of the fragment spin relative to the orbital angular momentum. Detailed studies using continuum gamma ray distributions¹ have shown that the alignment peaks at intermediate total kinetic energy losses (TKEL). However, some studies, which have used discrete gamma ray transitions, have also observed an increase in the alignment for the smallest energy losses.² In a recent experiment we have studied the dependence of fragment spin alignment on TKEL for both discrete transitions and the continuum. The continuum results are reported here.

The system studied was 684 MeV $^{80}\text{Kr} + ^{174}\text{Yb}$. The charge, energy and position of the projectile-like fragment was determined by means of a position sensitive ionization chamber (IC). The position of the target-like fragment was determined in a position sensitive parallel plate avalanche counter (PPAC). This information determines the two body kinematics and therefore allows for the calculation of the TKEL. In addition to the particle detectors described above, 6 Compton-suppressed intrinsic Ge detectors were used to detect coincident gamma rays. The continuum spectra were obtained by summing over 50 keV intervals. In the results shown here the discrete transitions have not been subtracted out.

The anisotropy (A) of the continuum spectra, defined as the efficiency corrected ratio of gamma ray yield perpendicular and parallel to the reaction plane normal, is shown in Fig. 1. The anisotropy approaches 1 for all TKEL bins, for both low and high gamma ray energies. This has been observed in previous continuum studies,¹ and is expected from the mixture of multipolarities which contribute to these parts of the gamma ray spectra.

Fig. 1. The gamma ray anisotropy (yield in-plane/yield out-of-plane) as a function of gamma ray energy for 10 bins in TKEL. These data are selected by requiring a Z=34 fragment in coincidence in the ionization chamber with a gamma ray. The histograms are offset from the 0 of the anisotropy axis by an increasing amount as the TKEL increases. The TKEL bins and offsets are: a) 0–25 MeV, 0; b) 25–50 MeV, 1; c) 50–75 MeV, 2; d) 75–100 MeV, 3; e) 100–125 MeV, 4; f) 125–150 MeV, 5; g) 150–175 MeV, 6; h) 175–200 MeV, 7; i) 200–225 MeV, 8; j) 225–250 MeV, 9. XBL 8512-5017

At intermediate gamma ray energies the anisotropy peaks at TKEL values of approximately 30 MeV and then again at approximately 150 MeV. The peak at large energy loss corresponds to that observed in previous continuum studies.¹ The peak at low energy loss may correspond to the large anisotropies observed in recent discrete line work. While the

rise and fall of fragment alignment for large energy losses is well understood,¹ the large alignment seen for the small values of TKEL is not understood at this time.

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K-Vacancy Production in High Energy U + U Collisions*

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We have measured total K-vacancy production probabilities in elastic U + U collisions at 7.5 and 8.56 MeV/nucleon for very small impact parameters ($b < 15$ fm). In these collisions the projectile velocity (v_i) is small compared to the velocity of the K-shell electron (v_e), $v_i/v_e \approx 0.2$, hence a molecular orbital (MO) description of the collision process should be applicable. The total K-vacancy production probability represents a sum of the vacancies produced in the $2p\sigma$ and $1s\sigma$ MOs, which are the two innermost MOs formed during the collision. Before and after the collision the $1s\sigma$ and $2p\sigma$ MOs correlate to the separated atom $1s$ level. K-vacancies are produced primarily via the $2p\sigma$ MO as it is less deeply bound than the $1s\sigma$ MO. We observe these vacancies decay as K x-rays in the separated U atoms after the collision.

A scaling law^{1,2} has been proposed for the K-vacancy production probability, P_K , as a function of $R_0(b)q_0$, where R_0 is the distance of the closest approach and

$$q_0 = E_K(R_0)/\hbar v_i \quad (1)$$

Here E_K is the binding energy of the $2p\sigma$ or $1s\sigma$ MO. The scaling law takes the form

$$P_K = F(Z_U) \exp(-mR_0q_0) \quad (2)$$

where F is a function of the united-atom atomic number ($Z_U = Z_1 + Z_2 = 184$ for U + U).

Armbruster *et al.*³ have shown that $1s\sigma$ ionization follows the scaling law for a variety of asymmetric collision systems and a range of projectile energies from below to just above the coulomb barrier and that $m \approx 2$ for $133 < Z_u < 178$. For Pb + Cm collisions they have determined that $m = 2.5$ for $2p\sigma$ ionization over a range of projectile energies from 3.6 to 5.9 MeV/nucleon.

In symmetric collisions one must estimate the $1s\sigma$ contribution to the ionization probability using the scaling law and then subtract this from the measured total K-vacancy production to determine the $2p\sigma$ ionization probability ($P_{2p\sigma}$). For $1s\sigma$ excitation in U + U one can take $m = 2$ and $F = 2$.² In this manner Molitoris, *et al.*, have shown that $2p\sigma$ ionization in U + U collisions is in reasonable agreement with the scaling law. Fits of that data to the scaling law have determined $m = 2$ and $F = 3.29 \pm 0.40$.

The present data for 7.5 and 8.56 MeV/nucleon U + U indicates an enhancement of the ionization probability for $R_0q_0 < 0.6$ (See Fig. 1), which corresponds to $b < 10$ fm in these collisions. Furthermore, the measured $2p\sigma$ ionization probability for

each projectile energy tends to converge with the scaling law prediction as b increases. It has been suggested^{5,6} that the increase in $P_{2p\sigma}$ toward small b could be due to rotational coupling of vacancies created in higher MOs ($2p_{5/2}, 2p_{3/2}$) to the $2p\sigma$ MO.

Footnotes and References

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Fig. 1. Present data at 7.5 and 8.56 MeV/nucleon along with the data of ref. 4. The solid line is a scaling law fit from ref. 4 with $m=2$ and $F=2.39$, the dashed line is another scaling law fit with $m=2.5$ and $F=3.32$.
XBL 8512-5019

Nuclear-Reaction-Time Studies of $^{238}\text{U} + ^{238}\text{U}$ Deep-Inelastic Collisions Via K-Shell Ionization*

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Several years ago Anholt¹ proposed that the theory of atomic inner shell ionization could be applied to the determination of nuclear reaction times in suitable deep inelastic reactions. If the K shell ionization probability PK is measured as a function of the total kinetic energy loss of the reaction $-Q$, the average nuclear time delay associated with a certain Q value can be deduced.

Recently Ch. Stoller *et al.*² inferred a nuclear delay time of approximately 10^{-21} s at $-Q=100$ MeV in the deep inelastic reaction $^{238}\text{U} + ^{238}\text{U}$ at a bombarding energy of 7.5 MeV/nucleon. This experiment relied on the unambiguous detection of two unfissioned U-like reaction products in coincidence. However, the detection of coincidences up to apparent $-Q$ values of ~ 250 MeV suggested that the

fission-rejection criteria may not have been stringent enough. We therefore repeated this experiment with a different detection method in order to improve fission event rejection and to extend the measurement to larger $-Q$ values. Incorrect fission event rejection falsifies not only the $-Q$ value but also the corresponding value of PK. The reason for this is that a U-like nucleus with large excitation energy will fission in a time ($\sim 10^{-21}$ sec) much shorter than the lifetime of a K vacancy ($\sim 10^{-18}$ to 10^{-17} sec). Hence, no U-like x ray will be emitted and PK is effectively reduced. Indeed, the entire PK dependence on $-Q$ can be fortuitously decreasing if the fission rejection decreases as $-Q$ increases.

Our experimental setup is shown in Fig. 1. The 7.5 MeV/nucleon ^{238}U beam from the SuperHILAC bombarded 600–750 $\mu\text{g}/\text{cm}^2$ ^{238}U targets. Particles emerging from the collision were detected by an ionization chamber on one side of the beam and by two parallel plate avalanche counters (PPACs) on the other side. The main element here is the LBL large-solid-angle ionization chamber³ which can determine $\Delta E_1 - \Delta E_2 - E_{\text{rest}}$, θ (in plane) and ϕ (out of plane) for the detected particle. In this chamber unfissioned U nuclei were unambiguously selected and from the energy and angle alone we determine $-Q$, independent of the behavior of the partner product. For the PK determination we used two large area PPACs to see if the reaction partner has fissioned or not. The front (transmission) PPAC allowed time of flight measurements in conjunction with the rear two dimensional position sensitive (stop) PPAC. The rear PPAC also provided a ΔE measurement. The uranium K x rays were detected by an 8mm thick intrinsic Ge planar detector directly opposite the PPAC arm of the experiment.

With our setup we can determine that one channel has fissioned and then compute $P_K^{(f)}$ or that both partners are intact and then we can find $P_K^{(U)}$. Delay times determined from our preliminary results in the measurement of $P_K^{(U)}$ are in qualitative agreement with the results of Stoller *et al.*² The measurement of $P_K^{(f)}$ could have some dependence on the fission lifetime, depending on whether or not the fissioning channel lives long enough for both molecular

orbitals formed during the collision ($1s\sigma$ and $2p\sigma$) to correlate to the $1s$ atomic level in uranium. Calculations⁴ indicate that at low excitation energies (< 13 MeV) the fissioning reaction product could live just long enough for the $2p\sigma$ MO to still correlate to the $1s$ level in the separate atom. If this is true $P_K^{(f)}$ will change abruptly at the $-Q$ value corresponding to that excitation energy. The determination of $P_K^{(f)}$ is presently in progress.

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Fig. 1. Experimental setup.

XBL 8512-5018

$^{139}\text{La} + ^{139}\text{La}$ at Intermediate Energies

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We have studied the reaction $^{139}\text{La} + ^{139}\text{La}$ at 40 MeV/nucleon with the purpose of elucidating the mechanism of complex and light particle production at intermediate energies. The complex fragments were detected by means of two Gas-Silicon-Plastic (GASP) multielement telescopes placed at 5° (GASP1) and -28° (GASP2) on opposite sides of the beams, while the light particles were detected in two silicon-plastic telescopes at 160° and four plastic-plastic telescopes at -5° to -20° .

Fig. 1 shows an E- ΔE plot of the events detected at 5° in GASP1. All the atomic numbers up to the target-projectile Z value (57) are represented with sizable probability, and their energy decreases gradually from the projectile Z value to lower Z values. In Fig. 2 the Z distributions from GASP1 and GASP2 are shown. The two distributions differ substantially, heavier fragments being clearly more favored at smaller angles. In Fig. 3 the invariant cross sections measured at the most forward angle for representative Z values are shown as a function of velocity. A characteristic peak is visible at beam velocity for the highest Z values, which broadens considerably with decreasing atomic number and there is even the hint of a lower velocity peak at $Z=15$.

Fig. 1. Density plot as a function of energy lost in the $\Delta E(\text{gas})$ and $E(\text{silicon})$ detectors, both in arbitrary units, for fragments detected from 4° to 6° in the GASP1 telescope. XBL 8512-4897

Fig. 2. Charge distributions for fragments detected at 5° and -28° . XBL 8512-9034

Fig. 3. Invariant cross section (arbitrary units) as a function of relative velocity for representative fragments detected at 5° . V_{beam} represents the beam velocity and V is the fragment velocity. XBL 8512-4896

The picture resulting from these data seems to be the following. At most impact parameters the projectile and target La nuclei survive as fairly excited fragments with a primary mass distribution still reflecting the original La nuclei. These fragments proceed to deexcite by means of conventional evaporation and complex particle emission. It seems possible that some of the highest Z values at small angles are evaporation residues from such primary fragments. It is very likely, however, that the bulk of the intermediate Z values is associated with a binary fission-like decay of the primary fragments. While this picture seems to be consistent with the charge

distributions in Fig. 2 and the velocity spectra in Fig. 3, a more detailed coincidence study is needed in order to characterize the process quantitatively.

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Radioactive Decay via Heavy Ion Emission*

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Seven nuclides are now known to decay by emission of ^{12}C or ^{24}Ne , with branching ratios ranging from 6×10^{-10} to $\sim 5 \times 10^{-13}$ relative to α decay. Fig. 1 compares measured branching ratios for these nuclides, along with upper limits for heavy ion emission for a number of other nuclides, with predictions based on unified models of tunneling decay.^{1,2}

With the exception of the original discovery by Rose and Jones³ and the measurement of ^{12}C emission by ^{226}Ra by the Orsay group,⁴ all of the data in Fig. 1 were obtained with plastic track detectors.⁵⁻¹⁰

The hindrance factor for heavy ion emission from even-odd nuclei relative to even-even nuclei is much greater for ^{12}C and ^{24}Ne emission than for α emission, as one can tell by comparing data with theory in Fig. 1.

Work in progress in collaboration with Ken Moody and Ken Hulet at LLNL is aimed at detecting ^{34}Si emission from ^{240}Pu and ^{241}Am . We then hope to detect ^{48}Ca or ^{46}Ar from Cf isotopes and begin to fill in the gap between ^{24}Ne emission and normal fission.

Fig. 1. Measured and calculated branching ratio for heavy ion emission relative to α decay. Nuclides for which no data exist are still under study.

XBL 8511-4606

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Was Radioactive Decay via Heavy Ion Emission Seen Forty Years Ago?

P.B. Price* and S.W. Barwick

Barwick *et al.*¹ pointed out recently that some old data on spontaneous fission half-lives of a number of nuclides may have to be reinterpreted as evidence for monoenergetic heavy ion emission. These data were obtained during and shortly after World War II using ionization chambers to associate fission activity with very energetic pulses.

Fig. 1 compares measured or predicted branching ratio for heavy ion emission relative to α decay with the old values of branching ratio for spontaneous fission relative to α decay taken from a compilation by Vandenbosch and Huizenga.² Only nuclides for which $B(SF/\alpha)_{old} < 10^{-10}$ and for which mass distributions of "fission" products were never measured have been plotted.

For several of the nuclides shown in Fig. 1 our conjecture is confirmed, because new measurements of $B(SF/\alpha)$ made with the same plastic track detectors used to measure $B(HI/\alpha)$ show that $B(SF/\alpha)_{new} \ll B(HI/\alpha) \approx B(SF/\alpha)_{old}$. For nuclides in the figure for which heavy ion emission has not yet been sought, the old data on $B(SF/\alpha)$ can be used to predict half-lives for heavy ion emission.

Fig. 1. Nuclides with $\lambda_{SF}/\lambda_{\alpha} < 10^{-10}$ and reported values for λ_{SF} but no mass yields. XBL 8510-4421

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Fossil Tracks of Alpha Particle Interactions in Minerals*

P.B. Price^{*} and M.H. Salamon[†]

Fossil tracks due to spontaneous fission of ^{238}U impurities in minerals were discovered¹ in 1962 and form the basis of the well-known fission-track dating technique. Fossil tracks due to recoil daughter nuclei released in α decay of nuclei in the Th and U decay chains were discovered² in 1967. We have recently discovered a third type of natural track due to nuclear interactions of α particles from radioactive impurities with nuclei in a mineral. These " α interaction tracks," being caused by nuclei with lower dE/dx than fission fragments, are a sensitive measure of mild thermal events in the geological history of a mineral. Our main interest in them, however, is that they are very similar in track structure and thermal stability to tracks that would be left by hypothetical monopole-nucleus bound pairs, and their presence at the calculated frequency in mica constitutes evidence that monopole tracks in such a mineral would not have been thermally erased.

Fig. 1 shows measurements of the lengths of naturally occurring tracks in a mica sample, clearly grouped into three types. Fig. 2 shows data on the ratio of concentration of interaction tracks relative to fission tracks as a function of ratio of α recoil tracks to fission tracks in micas with fission track ages from 450 to 900 million years. The arrow labeled "calc.1" refers to a calculation based on known cross section data for (α, n) and (α, p) reactions with Al and Si, two of the major constituents of mica. The main contribution is from interactions of the 8.8 MeV alphas from ^{212}Po in the ^{232}Th decay chain with Al nuclei. The arrow labeled "calc.2" refers to a calculation based on production rates of interaction tracks in micas that we irradiated with He ions of energies up to 12 MeV at the 88-Inch Cyclotron.

In our current monopole search,³ we used only mica samples in which $\rho_{\text{int}}/\rho_{\text{SF}} > 0.1$.

Fig. 1. Lengths of naturally occurring tracks intersecting an internal cleavage plane in muscovite mica, after an etch time of 4h in 48% HF at 20° C.

XBL 8510-4419

Fig. 2. Correlation of $\rho_{\text{int}}/\rho_{\text{SF}}$ with $\rho_{\alpha R}/\rho_{\text{SF}}$ in samples of mica with values of ρ_{SF} ranging from 40 to 1600 per cm^2 .

XBL 8510-4420

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Radioactive Decay of ²³²U by ²⁴Ne Emission*

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Using polyethylene terephthalate track-recording films, which are sensitive only to particles with $Z > 6$, we have detected for the first time the exotic radioactive decay mode in which an energetic ²⁴Ne nucleus is emitted. For ²³²U the branching ratio for ²⁴Ne emission relative to alpha decay is $(2.0 \pm 0.5) \times 10^{-12}$, which is close to the values predicted in unified models of tunneling decay by Poenaru *et al.*¹ and Shi and Świątecki.²

Fig. 1 shows the superb signal to noise ratio attained with a Cronar polyethylene terephthalate detector, and Fig. 2 compares the distribution of measured ranges of ²⁴Ne nuclei emitted from ²³²U with ranges expected for various Ne isotopes calculated from Q values.

Table I summarizes the results. As the last line of the table suggests, ²⁴Ne emission from ²³²U was almost certainly seen as far back as 1951 but was misinterpreted as spontaneous fission.

Table I. Measurements of ²⁴ Ne decay of ²³² U	
Events detected	31
Q (MeV)	62.3
Calc. range in Cronar (μm)	33.2
Measured mean range (μm)	32.8 ± 0.23
Branching ratio, $\lambda(^{24}\text{Ne})/\lambda(\alpha)$	
Measured	$(2.0 \pm 0.5) \times 10^{-12}$
Calculated (ref. 2)	4.87×10^{-11}
Calculated (ref. 1)	6.7×10^{-12}
Measured $\lambda_{\text{SF}}/\lambda_{\alpha}$ (ref. 3)	1.2×10^{-12}

Fig. 1. Photomicrograph showing head-on track due to a 56 MeV ²⁴Ne ion in Cronar detector. About 3×10^6 alpha particles passed through this field of view. XBB 8510-8634

Fig. 2. Ranges of ²⁴Ne nuclei determined from track lengths in Cronar detector. XBL 8510-4422

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Flow of Nuclear Matter*

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Collective flow has recently been observed in Nb + Nb collisions at 400 MeV/nucleon measured with the Plastic Ball.¹ Two collective effects, the side-splash of the participants and the bounce-off of the spectator nucleons have been established. Collective flow has been observed as well in collisions of asymmetric target projectile combinations measured with the Streamer Chamber.² In this report we are presenting data on collective flow for collisions of 150, 250, 400, 650 and 800 MeV/nucleon Au + Au and 400 MeV/nucleon Nb + Nb and Ca + Ca, again measured with the Plastic Ball spectrometer at the Bevalac. The events are analyzed with the kinetic energy flow method³ and the distributions of flow angles are discussed.

Since the charged particle multiplicity is related to the impact parameter, we classify the events according to the participant proton multiplicity (N_p), defined and used in ref. 4. The average multiplicity depends on the target-projectile mass and on the bombarding energy. In order to make meaningful comparisons the multiplicity bins chosen should correspond always to approximately the same range in normalized impact parameter. The best approach to reach that goal is to divide the multiplicity distribution into bins of constant fractions of the maximum multiplicity. The multiplicity distribution has roughly the same form for all systems and energies: a monotonic decrease with increasing multiplicity with a rather pronounced plateau before the final sharp decrease at the highest multiplicities. Therefore the

maximum multiplicity ($N_p^{\max}$) can be defined at the point where the curve drops to one half the plateau height. The data accumulated with a minimum bias trigger are then divided into 5 bins, 4 equal width bins between 0 and maximum multiplicity and one bin with multiplicities larger than $N_p^{\max}$.

For each event the flow analysis yields the angle of the major axis of the best fit ellipsoid relative to the beam axis (flow angle θ) and the aspect ratios. Both kinds of values are influenced and distorted by fluctuations. Even for multiplicities as high as 100 charged particles the distortion of the aspect ratios is still larger than 30%,⁵ whereas the amount of directed energy flow in the data has been estimated to be of the order of 10% of the energy available in the center of mass system.¹ Therefore, it can not be expected that the aspect ratios contain useful information. In fact, within the stated limitations the aspect ratios for the highest multiplicity events are compatible with isotropic emission. Consequently we obtain essentially one parameter, the flow angle, as a result of the energy flow analysis. However, the Jacobian free distribution⁵ $dN/d(\cos \theta)$ of the measured angles is easily calculated.

The distribution of the flow angles for Ca + Ca, Nb + Nb and Au + Au, at 400 MeV/nucleon is shown in Fig. 1. The trend toward larger flow angles as the target-projectile mass increases has been reported before¹ and clearly continues going from Nb to the heaviest system measured thus far, Au + Au. An increase with mass has been predicted qualita-

tively by Vlasov-Uehling-Uhlenbeck calculations,⁶ however, that predicted increase is more pronounced than the one observed here. For a quantitative comparison a careful analysis including the effects of experimental efficiency and acceptance has to be performed.

Also important is the energy dependence of the flow angles. This is shown in Fig. 2 for 5 different Au + Au energies from 150 MeV/nucleon up to 800 MeV/nucleon. The general trend observed is that the flow angle decreases with increasing energy above 250 MeV/nucleon. At the lowest energy the reaction mechanism responsible for the flow effect might lose importance in favor of other mechanisms known from low energy heavy ion reactions. In addition, the division into bins of constant fractions of the maximum multiplicity might not be appropriate at 150 MeV/nucleon since the maximum multiplicity indicates that total disintegration of projectile and target is not yet reached even for the most violent collisions.

Fig. 1. Jacobian free distributions of the flow angles ($dN/d\cos\theta$) for the systems Ca + Ca, Nb + Nb and Au + Au all at 400 MeV/nucleon. XCG 857-356

Fig. 2. Jacobian free distributions of the flow angles for the system Au + Au at 5 different energies

XCG 857-354

The fact that the flow angles become smaller with increasing energy does not indicate that the flow effect gets smaller; it means, however, that the mean transverse momentum does not increase quite as fast as the longitudinal momentum. On the contrary, since the decrease in angle is only small, it is possible that the mean perpendicular momentum transfer increases with energy. If one is allowed to relate the collective perpendicular momentum transfer to the pressure built up, then that would indicate that the pressure increases with energy.

The observation of collective flow in the data indicates that a pressure buildup has developed during the collision. However, the question of whether that pressure is due only to kinetic effects from the heating of matter and to fermi motion or whether that pressure is due to potential energy effects cannot be answered by the experiment alone. A very careful quantitative comparison of the experimental results with model predictions has to be performed where all the effects of experimental efficiency and acceptance have to be taken into account.

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Progress in MST Analysis of Plastic Ball Events

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In order to investigate the influence of target and projectile spectator particles on the deduced flow angles in Plastic Ball events for relativistic heavy ion (HI) reactions, an efficient method to identify those particles is needed. We applied the cluster algorithm "minimal spanning tree" (MST)^{1,2} and determined its discriminating power by analyzing model events from the statistical event simulation code of Fai and Randrup and from the Yariv Fraenkel Cascade code including spectator evaporation. First we restricted the analysis to uniquely defined "2-cluster" events, i.e., events in which two clusters oriented back to back can be identified and are related to projectile and target. If the identified spectator remnants are removed from the complete event we can hope to find a rather undisturbed participant distribution to which the flow analysis may be applied. The result of such a procedure applied to experimental data is discussed in the plane of the projection of the transverse momentum as a function of the center of mass rapidity for participant particles. The off-plane contour lines appear quite isotropic contrary to the in-plane contours which prominently show the preferred emission angle around 30°. The corresponding flow angle distribution shows a peak at 25° which is higher by about 50% compared to the correspond-

ing analysis where spectators are included (Nb + Nb 400 MeV/nucleon.)

In the meantime the analysis was generalized and extended to "n-cluster" events, i.e., events in which at least one spectator cluster can be efficiently identified and the artificially generated clusters can be rejected. We investigated several definitions of the distance measure $d_{ij}(\Delta Y, \Delta \theta, \Delta p_{\perp})$ containing the difference in rapidity, angle and transverse momentum between two particles i and j in the event. Fig. 1 shows a typical efficiency distribution deduced from simulated events. Participant particles are identified on a level of 90% to 95% independent of the multiplicity, whereas the efficiency for spectator fragment identification decreases from 85% to about 75% depending on cluster number and multiplicity. The results are rather insensitive to details in the definition of d_{ij} .

From the analysis of the azimuthal angle of the projectile spectator cluster the reaction plane can be determined. Several definitions of ϕ -angles such as thrust angle, flow angle or transverse momentum distribution were investigated. The best result was obtained with the transverse momentum method allowing a determination of the reaction plane within 30° (FWHM).

Fig. 2 shows in comparison to the full multiplicity distribution (solid line) of Fai-Randrup statistical events the corresponding distributions for those events accepted by the MST algorithm. The restriction to "2-cluster" events (Fig. 2, dotted line), allows the analysis of a small subset ($\approx 10\%$) of all events. The extension to "n-cluster" events (Fig. 2, dashed line), however, with a suitable rejection of artificially generated clusters, accepts roughly 50% of all simulated events in a wide range of multiplicities. After these rather detailed investigations, the MST algorithm seems to be a reliable and useful tool in the analysis of complete events from relativistic HI reactions.

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Fig. 1. Efficiency of the cluster algorithm versus cluster number. The values plotted at cluster number zero correspond to the average over all cluster numbers. XBL 8510-4189

Fig. 2. Charged particle multiplicity distribution for Fai-Randrup events (see text). XBL 8510-4190

Yield of Unbound ${}^5\text{Li}$ in Relativistic Nuclear Collisions

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We have looked with the Plastic Ball 4π detector for correlations between p,d,t, ${}^3\text{He}$ and ${}^4\text{He}$, and have found a number of easily observable correlations with low relative kinetic energies corresponding to known nuclear resonances.¹ One approach taken in understanding these correlations has been to treat them strictly as unbound resonances and determine

the population of the resonance with chemical equilibrium models or other statistical models. It is of particular interest to test the Quantum Statistical Model (QSM) of H. Stöcker *et al.*,² since it is being used in conjunction with measured relative yields of bound clusters to determine entropy.^{3,4} This model predicts yields for both bound and unbound clusters,

so two particle correlations provide an additional consistency check of this approach.

The ${}^5\text{Li}$ ground state yield was extracted from the strong enhancement observed in the p - ${}^4\text{He}$ pair yield at the appropriate relative energy. This was for the system $\text{Ca} + \text{Ca}$ at 400 MeV/nucleon. The ratio of ${}^5\text{Li}$ divided by the number of participant protons (corrected for the estimated Ball efficiency of 39%) is shown in the figure. In addition, the ratio of bound fragment yields to participant proton yields are shown as a function of total participant protons in the event (including protons bound in light clusters), referred to here simply as proton multiplicity. The yield of clusters relative to protons shows a clear trend of increase with proton multiplicity. That is, the relative yield for clusters increases as the collisions become more central with increased amounts of nuclear matter in the participant or overlap region. The curves appear to be approaching a saturation value which can be compared with chemical equilibrium model fragment yields for infinite nuclear matter. In the figure we show the results of the Quantum Statistical Model (QSM) of H. Stöcker *et al.*² where the entropy, the controlling parameter of this model, has been chosen to give plausible extrapolated yields for the bound clusters shown. At this point it is difficult to directly compare our ${}^5\text{Li}$ value with the QSM prediction shown since the measured yield was averaged over proton multiplicity values. Future analysis will rectify this problem, but we can anticipate a dependence of ${}^5\text{Li}$ yield on proton multiplicity similar to the bound clusters shown. In this case the QSM would appear to do as well describing the unbound ${}^5\text{Li}$ yield as the bound clusters. It is of interest in the future to pursue these comparisons in more detail since the QSM is a promising tool for measuring entropy.

Footnotes and References

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Fig. 1. The yields of bound clusters $d, t, {}^3\text{He}$ and ${}^4\text{He}$ divided by the number of unbound participant protons are shown as a function of n_p , the total number of participant protons (bound and unbound). Also shown is the yield of the unbound ${}^5\text{Li}$ ground state divided by the number of unbound participant protons. This point is shown as the mean n_p value for the sample studied. The corresponding ratios from the Quantum Statistical Model of H. Stöcker

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Cluster and Entropy Production in Relativistic Nuclear Collisions*

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There are calculations¹⁻⁴ showing that composite particle production determines the size of the participant volume at freeze out and that the ratio of deuterons to protons can be related to the produced entropy in the system.⁵⁻⁷

From the data taken at the Bevalac with the Plastic Ball/Wall spectrometer we have determined the d/p ratios as a function of the participant baryon charge multiplicity for the two systems Ca + Ca and Nb + Nb at different energies. The functional form of these ratio curves can be understood in terms of the coalescence model.^{1,4,8} To determine the size of the participant volume and the freeze out densities we have used an improved version of the model.³ The extracted freeze out densities are shown in Fig. 1a and they vary between 0.5 and 1.0 times normal nuclear matter density.

To relate the production of composites to the produced entropy in the system we have used the models by Kapusta⁶ and Stöcker.⁷ Both models are calculations for infinite nuclear matter and use the asymptotic values of the d/p ratios to determine the produced entropy. The extracted entropy values using these models are shown in Fig. 1b. The lower points are from the model by Stöcker⁷ and the upper ones from the model by Kapusta.⁸ The most striking feature of Fig. 1b is the big difference in the entropy obtained from the two models, even though the basic physics going into the two models is essentially the same. Figure 1b shows that the extracted entropies are strongly model dependent.

The entropy produced in the reaction contains information on the equation of state but without an observable for the density reached, one is forced to rely on models relating the bombarding energy to the density. In the fireball model⁸ all kinetic energy goes into thermalization. For a density equal to normal nuclear density, this results in entropy values shown in Fig. 2 as the dashed curve. As can be seen, the

Fig. 1. a) Chemical freeze out densities and b) entropy per nucleon (S/A) as a function of bombarding energy for the two systems Ca + Ca at 400 and 1050 MeV/nucleon (filled points) and Nb + Nb at 400 and 650 MeV/nucleon (open points). The smaller error bars are from statistics only. XBL 853-8064

fireball model predicts too much entropy compared to that extracted from data using the model in ref. 7.

In the hydrodynamical model some of the kinetic energy goes into compressional energy and such a calculation with an equation of state based on the relativistic mean field theory of ref. 9 is shown as the solid curve in Fig. 2. The agreement is very good with the experimentally extracted entropy values⁷ showing that compression has to be present to explain the produced entropy in the collisions.

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Fig. 2. (a) Entropy per nucleon (S/A), extracted using the model of Stöcker⁷ and (b) the experimentally determined apparent temperatures at maximum proton multiplicity as a function of bombarding energy (the symbols have the same meaning as in Fig. 1.)

XBL 853-10132

Study of Relativistic Nucleus-Nucleus Collisions at the CERN SPS: WA-80

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This experiment will use 60 and 225 GeV/nucleon beams of ^{16}O and ^{32}S at the CERN Super Proton Synchrotron in December 1986 and May 1987. The primary physics goals of WA-80 are:

1. survey of high energy light ion-nucleus collisions on various targets and comparison with pion and

proton-nucleus collisions;

2. search for indications of the formation of the quark gluon plasma (QGP) or similar phase transitions;
3. determination of nuclear stopping power and thus the maximum baryon density limit.

Fig. 1 shows the general layout of the experiment. It consists of five major pieces of equipment: the Plastic Ball, SAPHIR (Single Arm Photodetector for Heavy Ion Reactions), the Wall Calorimeter, the Multiplicity Array, and the Zero Degree Calorimeter. In addition there is a vacuum pipe containing a Beam Counter upstream and a Bull's Eye Detector (Trigger counter) at the exit.

The *Plastic Ball*, presently in operation at the Bevalac, consists of 655 ΔE -E telescopes and will detect target rapidity fragments from protons through alphas, and also π^+ . The 160 modules of the Mall will not be used. The matter flow in the target rapidity region will be determined from a global analysis approach. If finite flow angles are observed then the reaction plane is defined and, together with the Ball multiplicity measurement, the impact parameter can be deduced.

SAPHIR is a lead glass calorimeter for π^0 and direct gamma identification consisting of 1350 modules. The modules of SF5 lead glass are 48 cm long and 3.5 x 3.5 cm at the front face. It will be placed under the beam line at $8^\circ \leq \theta \leq 18^\circ$ and cover approximately ± 40 degrees in azimuthal angle. A streamer tube multiplicity detector will serve for charged particle discrimination. SAPHIR will study π^0 and single photons at intermediate to large $p_\perp$ near 90° in the nucleon-nucleon center of mass. The use of Pb-glass Čerenkov detectors in a finely segmented array helps to suppress the low energy soft particles and allows the identification of single gamma rays in the presence of a large background of gammas from π^0 decay. The observation of direct gamma production may be one of the signatures of a QGP.

The six square meter *Wall Calorimeter* at a distance of 6.5 m from the target will detect mid-rapidity baryons and pions. It is only slightly modified from the Fabjan-Willis design used at CERN. It consists of 150 towers with a lead-scintillator electromagnetic section ($15 L_{rad.}$) and a stainless steel-scintillator hadronic section ($6.2 \lambda_I$). The Wall

Fig. 1. The general layout of experiment WA-80.

XBL 859-4097

Calorimeter will study the transverse energy distribution $dE_\perp/d\eta$ in the mid-rapidity region as a function of the number of participants.

The *Multiplicity Array* will determine the pseudorapidity of all charged particles. The Large Angle Multiplicity Detector will cover the angles from 9 to 30 degrees. Just behind this will be one covering the area of SAPHIR and further downstream the Mid Rapidity Calorimeter Multiplicity Detector, consisting of a double layer (for 100 percent efficiency), will be placed in front of the Wall Calorimeter. They will be made of streamer tubes of the Iarocci type with pad readout setting a bit for each of the 25,000 cells. These Multiplicity Arrays will carefully measure in geometrical detail all charged particles in θ and ϕ .

The *Zero Degree Calorimeter* will measure the total kinetic energy of the projectile fragments for use in the trigger. It contains both electromagnetic and hadronic sections, both consisting of uranium-scintillator. The dimensions are larger than a tower of the Wall Calorimeter. Its main purpose will be to provide a trigger for the other components of the experiment. Thus, it will determine whether or not the projectile has undergone any type of interaction with a target nucleus. In more detail the study of nuclear stopping will look for the existence of leading particles as a function of target nucleus thickness.

The *upstream Beam Counter* will identify the projectile (from protons to ^{40}Ca) and generate the timing signal which will become the trigger. The *Bull's Eye Detector* at the exit of the vacuum pipe downstream of the target will measure the sum of the square of the nuclear charges of the projectile fragments for use in the trigger. Both detectors will probably be Čerenkov counters and are being developed.

Footnotes and References

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Multiplicity Selected Single Particle Observations

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It is now well established at the Bevalac that large numbers of particles in the final state are a useful signature of central collisions. Central nucleus-nucleus collisions provide us with a unique opportunity of studying nuclear matter under extreme conditions of temperature and/or compression.

In order to gain more insight into the dynamics of these collisions we have added a 112 element multiplicity array to the beam 30-2 single arm magnetic spectrometer of Nagamiya and collaborators at the Bevalac Facility. The multiplicity detector consists of three separate sections of scintillation counters, each section covering the full azimuthal acceptance ($\Delta\phi=360^\circ$) about the production target. The laboratory angular coverage ($\Delta\theta_{\text{lab}}$) for these segments was: $\Delta\theta_{\text{lab}}=10-25^\circ$, $25-44^\circ$, and $44-90^\circ$. Two scintillators were left out of each section to reduce the amount of material traversed by a produced particle ($\pi^\pm$, p, d, t, ^3He , ^4He) as it entered the magnetic spectrometer.

Experiment 738H was carried out to study the production of subthreshold charged pions and energetic light nuclear fragments for $^{139}\text{La}+^{139}\text{La}$ collisions at 137, 183 and 246 MeV/nucleon with associated multiplicity information. A charged particle in the spectrometer provided the main trigger for each event. The individual multiplicity array elements for that event were then recorded so that off-line cuts

could be made to investigate the various particle spectra for different ranges of associated multiplicity, the centrality of the collision being proportional to the multiplicity. Fig. 1 shows a sample event in which a subthreshold π^- was produced in a $^{139}\text{La}+^{139}\text{La}$ collision at 246 MeV/nucleon. The hits on the wire chambers indicate the trajectory of the π^- in both the horizontal and vertical planes. The individual elements of the multiplicity detector are also shown. Note that over 70% of these elements were struck by charged particles emitted in this single event, suggesting that this particular negative pion was produced in a relatively central collision. Fig. 2 shows preliminary results from 738H for a multiplicity selected proton spectrum ($\theta_{\text{cm}}=90^\circ$). The higher multiplicity events have a flatter spectrum, as would be expected if they were produced in a more central collision (more participant matter). Further studies are underway to use multiplicity correlations as a tool for unraveling the precise details of the dynamics governing these collisions.

Footnotes and References

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Fig. 1. Computer schematic showing a π^- trajectory through the magnetic spectrometer. The hit pattern on the 3-section (innermost array corresponding to most forward angles) is indicated. XBL 8512-12844

Fig. 2. Preliminary results from Experiment 738H for La+La $\rightarrow p(\theta_{cm}=90^\circ) + x$ spectra for two different multiplicity cuts. The inverse slope parameters, T_0 , from a fit to $d\sigma/dp^3 \propto e^{-T/T_0}$ are indicated.

XBL 8512-12843

Pion Interferometry Studies of Relativistic Heavy-Ion Collisions Using the Intranuclear Cascade Model*

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A method is presented by which an intranuclear cascade (INC) model may be used to obtain pion source parameter predictions which can be directly compared with pion interferometry experiments. This method is applied with Cugnon's model to extract predictions for recent pion interferometry

measurements, and generally good agreement is found.

Footnotes and References

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Pion Source Parameters in Heavy Ion Collisions*

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Following the early work of Goldhaber, Goldhaber, Lee, and Pais,¹ many experiments have used the momentum correlations between identical bosons to determine the space-time extent of the pion source for various reactions between elementary hadrons. This technique, known as intensity interferometry, has recently been applied to nuclear collisions at both intermediate²⁻⁴ and very high energies.⁵ Here we report on measurements of the radius and lifetime of the pion source in the reactions 1.8 GeV/nucleon $^{40}\text{Ar}+\text{KCl} \rightarrow 2\pi^\pm + \text{X}$, 1.8 GeV/nucleon $^{20}\text{Ne}+\text{NaF} \rightarrow 2\pi^\pm + \text{X}$, and 1.7 GeV/nucleon $^{56}\text{Fe}+\text{Fe} \rightarrow 2\pi^\pm + \text{X}$.

In principle, intensity interferometry can provide a detailed picture of the size, shape and lifetime of the pion source, as well as determining the extent to which the pion emission process is a coherent one.⁶ Assume that the pion source distribution is well-approximated by the form

$$\rho(r,t) \propto \frac{1}{\pi^2 R^3 \tau} e^{-\frac{r^2}{R^2} - \frac{t^2}{\tau^2}} \quad (1)$$

The fundamental result of intensity interferometry⁶ states that the correlation function $C_2(q,q_0)$, defined as the ratio of the two-particle inclusive probability to the product of the single-particle probabilities, is given by

$$C_2(q,q_0) = 1 + \overline{\rho}(q,q_0)^2 \quad (2)$$

where $\overline{\rho}(q,q_0)$ is the Fourier transform of $\rho(r,t)$ with respect to q where q_0 , and q,q_0 are, respectively, the magnitudes of the momentum difference and the energy difference of the two pions.

The experiment used the Bevalac to produce beams of 1.8 GeV/nucleon ^{40}Ar , incident on a KCl target; 1.8 GeV/nucleon ^{20}Ne incident on a NaF target; or 1.7 GeV/nucleon ^{56}Fe incident on stainless steel and natural Fe targets. Pions produced at $(45 \pm 8)^\circ$ in the laboratory were accepted into a broad-band magnetic spectrometer. For the Fe + Fe measurements, an additional dipole magnet was placed at the target position so that pions produced

near 0° could be studied. Four MWPCs with 2 mm wire spacing determine the momentum of accepted pions to better than 2% for $\vec{P}_{\text{lab}} > 200 \text{ MeV/c}$.

A scintillator hodoscope is used to provide a two-pion trigger for each event. The geometric overlap of the "A" counters with "B" counters defined a set of 17 possible AB combinations. A good two-pion trigger was defined as the presence of any two (different) AB combinations in conjunction with signals from the "S" counters and the MWPCs. The time of flight and pulse height in each of these counters are recorded to allow for off-line background rejection. In the case of the $^{40}\text{Ar}+\text{KCl}$ system both $2\pi^-$ and $2\pi^+$ data were taken, while for the $^{20}\text{Ne}+\text{NaF}$ and $^{56}\text{Fe}+\text{Fe}$ only $2\pi^-$ triggers were used. On the order of 10^4 two-pion pairs were analyzed for each of these pion polarities and target-projectile combinations.

Off-line analysis uses geometric criteria to identify good track candidates. These candidates are further selected by parameterizing each particle's vector momentum and initial target location in terms of MWPC hit coordinates. This parameterization is obtained by fitting Monte Carlo generated data with a Chebyshev expansion. The intrinsic precision of this procedure is very high, so that the final momentum resolution is completely determined (for low energy pions) by multiple scattering in the target, the air, and the detectors; or (for high energy pions) by the finite spatial resolution of the MWPCs.

Events containing a pair of accepted pions are used to generate the correlation function. Each pion in a good pair event is required to have $150 \text{ MeV/c} < \vec{P}_{\text{lab}} < 800 \text{ MeV/c}$, which provides a sample of events with high momentum resolution and very low proton contamination ($< 2\%$). The correlation function is created from these events by dividing the number of actual pairs in a q and q_0 bin, $A(q,q_0)$, by the number of background pairs in the same bin, $B(q,q_0)$.

The background events are generated by combining individual pions taken from different good two-pion events. Intuitively, it would appear that this procedure for creating the background removes all correlations between particles in the background, while accurately reflecting the effects of the spectrometer acceptance. However, it is straightforward to demonstrate that a residual influence of the correlations found in the real events persists in the $B(q, q_0)$ generated by mixing pions from different events.⁷ Extraction of the correlation function from the ratio of $A(q, q_0)$ to $B(q, q_0)$ therefore involves an iterative procedure. Also included in this iteration procedure is the effect of the Coulomb repulsion between the two like pions. Since this repulsion is maximal for those events where $q=q_0$, and since many of our events have $q \approx q_0$, it is essential that this effect be included in the analysis procedure. A detailed account of the Coulomb corrections and the iteration method may be found in ref. 7.

Given in Table I are the results of fitting the correlation functions to the form

$$C_2 = \alpha \left(1 + \lambda e^{-\frac{1}{2} q^2 R^2 - \frac{1}{2} q_0^2 \tau^2} \right) \quad (3)$$

which, aside from the parameter λ , is the C_2 corresponding to the source density given by eq. (1). The parameter α is used to renormalize the C_2 's so that their asymptotic value is one. The parameter λ , which would be unity for a perfectly chaotic (i.e., incoherent) pion source, is left free to avoid introducing systematic errors in the determination of R and τ . The values obtained for λ are substantially less than unity. However, the iterative procedure used to calculate the correlation functions introduces systematic errors in the determination of λ that prohibit any strong statement concerning the significance of this result. The measurement of R and τ are much less subject to these difficulties, so that the statistical error is the dominant error in determining these quantities. The errors quoted in all cases are statistical only.

In analyzing the Fe+Fe data, we assumed the pion source was axially symmetric, such that eq. (1) is now expressed in terms of the parameters $R_\perp$, R

and τ , the radius parameters transverse and longitudinal to the beam direction, and the lifetime parameter, respectively. This changes the functional dependence in eqs. (2,3) such that $(q, q_0) \rightarrow (q, q_\perp, q_0)$; otherwise the analysis methods are the same as described above.

The experimental results for Fe+Fe have been compared with predictions for the pion source parameters obtained from ref. 8 using Cugnon's CASCADE code. A highly oblate source ($R_\perp > R$) is measured both for the 45° and for the 0° geometry; Cugnon's CASCADE is seen to agree with the 45° data, while for the 0° data agreement between the experiment and CASCADE is less convincing. Within the context of CASCADE, oblate shapes can be shown to result from the shadowing of pions by nuclear matter present in the collision.⁸ Data have been taken with $\text{La+La} \rightarrow 2 \pi^- + X$ and the analysis is in progress.

Footnotes and References

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Table I
Pion Source Parameters for 45° and 0° Data

45° data	$R_{\parallel}(\text{fm})$	$c\tau(\text{fm})$	λ	χ^2/NDF
Ar + KCl $\rightarrow 2\pi^- + X$	$2.88_{-1.6}^{+0.5}$	$3.29_{-1.6}^{+1.4}$	0.63 ± 0.04	98.2/80
Ar + KCl $\rightarrow 2\pi^+ + X$	$4.20_{-0.6}^{+0.4}$	$1.54_{-1.54}^{+2.4}$	0.73 ± 0.07	67.1/81
Ne + NaF $\rightarrow 2\pi^- + X$	$1.83_{-1.6}^{+0.8}$	$2.96_{-1.0}^{+0.9}$	0.59 ± 0.08	125.7/82
$R_{\parallel} = 1.5_{-0.9}^{+0.3}$				
Fe + Fe $\rightarrow 2\pi^- + X$		$1.5_{-1.5}^{+1.1}$	$0.65_{-0.03}^{+0.05}$	652/486
$R_{\perp} = 4.8_{-0.5}^{+0.3}$				
0° data	$R(\text{fm})$	$c\tau(\text{fm})$	λ	χ^2/NDF
$R_{\parallel} = 0.01_{-0.01}^{+1.1}$				
Fe + Fe $\rightarrow 2\pi^- + X$		3.1 ± 0.5	$0.72_{-0.02}^{+0.06}$	822/485
$R_{\perp} = 5.0 \pm 0.4^{\ddagger}$				

$^{\dagger}R_{\parallel}$ Source dimension parallel to beam direction

$^{\ddagger}R_{\perp}$ Source dimension perpendicular to beam direction

Measurements of Interaction Cross Sections and Radii of He Isotopes*

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In this paper we report the first results of measurements of interaction cross sections using secondary beams of all known He isotopes. The nuclear matter radii of He isotopes, ^3He , ^4He , ^6He , and ^8He , have been deduced from the interaction cross sections.

Secondary beams of He isotopes were produced through the projectile fragmentation of 800 MeV/nucleon ^{11}B primary. Rigidity separated isotopes were then guided to the HISS (heavy ion spectrometer system) experimental area.

The interaction cross section (σ_I), defined as the total cross section for the process of nucleon (proton and/or neutron) removal from the incident nucleus, was measured by a transmission type experiment us-

ing the HISS spectrometer. Interaction cross sections at 790 MeV/nucleon were measured by all the known He isotopes (^3He , ^4He , ^6He , and ^8He) on Be, C, and Al targets (see Table I). We define an interaction nuclear radius by the equation,

$$\sigma_I(p,t) = \pi(R(p) + R(t))^2, \quad (1)$$

where $R(p)$ and $R(t)$ are the radii of the projectile and the target nuclei, respectively. Under the definition of eq. (1), the difference of the radii between ^4He and ^3He was calculated as,

$$R(^4\text{He}) - R(^3\text{He}) = \sqrt{\sigma_I(^4\text{He}, T)/\pi} - \sqrt{\sigma_I(^3\text{He}, T)/\pi} \quad (2)$$

where T denotes a target nuclei. The radius differ-

ences of ^AHe thus obtained are shown in Fig. 1. It is noted that the radius differences are essentially independent of target nuclei (except one case in ^4He) within ± 0.02 fm, supporting that the target and the projectile parts are separable as defined in eq. (1).

The absolute value of the ^4He radius was calculated to be $R(^4\text{He})=1.40\pm 0.05$ fm from the existing data of the $^4\text{He}+^4\text{He}$ and $^{12}\text{C}+^{12}\text{C}$ cross sections¹ and the present value of the $^4\text{He}+^{12}\text{C}$ cross section. The scale of the absolute value thus derived is also shown on the right-hand side of Fig. 1. The He radii thus determined are:

$$\begin{aligned} R(^3\text{He}) &= 1.59 \pm 0.06, \\ R(^4\text{He}) &= 1.40 \pm 0.05, \\ R(^6\text{He}) &= 2.21 \pm 0.06, \\ R(^8\text{He}) &= 2.52 \pm 0.06 \text{ in fm.} \end{aligned}$$

The dotted curve in Fig. 1 shows the $A^{1/3}$ dependence of nuclear radii. It is seen that the radii of ^6He and ^8He show larger increase than $A^{1/3}$ from ^3He . The radius of ^3He is larger than that of ^4He , in agreement with the known electron-scattering data.² The rms, $\sqrt{\langle r^2 \rangle}$, and half density, $r_{0.5}$, charge radii determined from the electron scattering are also shown for ^3He and ^4He in the figure. It is seen that the presently determined radii appear between $\sqrt{\langle r^2 \rangle}$ and $r_{0.5}$. The rms radii of He isotopes were calculated by a Hartree-Fock method using the Skyrme potential.³ The results showed a reasonable increase of the radius from ^4He to ^6He ; however the further increase from ^6He to ^8He was not well reproduced. The radii were also calculated by a Hartree method based on relativistic field theory,⁴ which showed that the symmetry energy played an important role to reproduce the radii of large $(N-Z)/(N+Z)$ nuclei such as ^6He and ^8He .

Footnotes and References

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Fig. 1. Radius differences of the ^AHe isotopes from ^3He . The absolute value of the radius is also shown on the right-side axis. A dotted curve shows the $A^{1/3}$ dependence of nuclear radii. The rms $\sqrt{\langle r^2 \rangle}$ and half-density $r_{0.5}$ charge radii determined from electron scattering are also shown for comparison. The uncertainty on the right-side scale indicated is not applied to the electron-scattering data.

XBL 8412-5232

Table I				
Interaction Cross Sections (σ_I) of He Isotopes				
σ_I in mb				
target	beam			
	^3He	^4He	^6He	^8He
Be	498 ± 4	485 ± 4	672 ± 7	757 ± 4
C	550 ± 5	503 ± 5	722 ± 6	817 ± 6
		527 ± 26^a		
Al	850 ± 9	780 ± 13	1063 ± 8	1197 ± 9
^4He		262 ± 19^a		

^adata from ref. 1. Present value of $^4\text{He}+\text{C}$ cross section agrees with the known value within quoted errors.

Measurements of Interaction Cross Sections and Nuclear Radii of Li Isotopes*

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In the present experiment we have measured the interaction cross sections for all the known Li isotopes (⁶Li, ⁷Li, ⁸Li, ⁹Li, and ¹¹Li,) and ⁹Be on target nuclei Be, C, and Al at 790 MeV/nucleon. Nuclear radii of these isotopes have been deduced from the interaction cross sections. The secondary beams of ¹¹Li and ⁹Be were produced through projectile fragmentations of the 800 MeV/nucleon ²⁰Ne primary beam. The other Li isotopes were produced from a ¹¹B primary.

The measured cross sections are listed in Table I. The errors shown in the table include the counting statistics as well as the systematic errors. The largest systematic error, which is about 0.3% of σ_I , was due to uncertainty in estimating the scattering-out probability. All other systematic errors were estimated to be less than 0.2% of the σ_I .

Table I			
Interaction Cross Sections (σ_I) in mb			
beam	Be	target C	Al
⁶ Li	651 ± 8	688 ± 13	1010 ± 11
⁷ Li	686 ± 4	736 ± 6	1071 ± 7
⁸ Li	727 ± 6	768 ± 9	1147 ± 18
⁹ Li	739 ± 5	796 ± 6	1135 ± 8
¹¹ Li		1056 ± 30	
⁹ Be	755 ± 6	806 ± 9	1174 ± 11

The listed errors include statistical and systematic errors. The largest systematic errors were due to uncertainties in the estimation of scattering-out probabilities of non-interacting nuclei.

The interaction nuclear Radius R_I is defined as,

$$\sigma_I(p,t) = \pi[R_I(p) + R_I(t)]^2 \quad (1)$$

where $R_I(p)$ is the radius of the projectile and $R_I(t)$ is that of target. The separability of projectile and target radii is the assumption made in the equation, which were examined by using σ_I of various projectile-target combinations, and were confirmed to be valid within ± 0.02 fm.

The R_I 's of Li isotopes as well as those of He isotopes are plotted in Fig. 1, where values obtained from the Be, C, and Al targets were averaged and the interaction cross sections of He isotopes were taken from ref. 1. The absolute scale of the radius is determined from a least squares fitting of ⁴He + ⁴He, ⁹Be + ⁹Be, ¹²C + ¹²C, ⁴He + ¹²C, and ⁹Be + ¹²C interaction cross sections.¹⁻³ The radii of ⁹Be and ¹²C are also plotted.

Fig. 1. Interaction nuclear radii R_I are plotted for all the He and Li isotopes as well as for ⁹Be and ¹²C. Dotted lines in the figure show the $A^{1/3}$ dependence of the radii. Differences of radii between pairs of isobars are seen for the first time. XBL 856-2809

For the first time we can directly compare the differences of radii between pairs of isobars, i.e. $R_I(^6\text{He}) - R_I(^6\text{Li}) = (0.10 \pm 0.03)$ fm, $R_I(^8\text{He}) - R_I(^8\text{Li}) = (0.12 \pm 0.03)$ fm, and $R_I(^9\text{He}) - R_I(^9\text{Be}) = (0.08 \pm 0.04)$ fm. The larger radii of the neutron rich isotopes ^6He and ^8He , which have only two protons, suggest the existence of thick neutron skins.

The semiclassical optical model has been shown to give the *rms* radius which is consistent with that obtained from the electron scattering. It has also been shown that the R_I gives a constant density ($\rho \approx 0.045 \text{ fm}^{-3}$) radius of a nucleus. It is thus demonstrated that the measurement of σ_I combined with the appropriate model calculation provides a new method to study the nuclear density distribution of stable isotopes and unstable isotopes which could not be accessed before.

Looking for Anomalons with a Segmented Čerenkov Detector*

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This experiment was the second run of E676H¹ in which we upgraded the Čerenkov counters from lucite to BK7W optical glass. In the previous experiment we used 3mm thick lucite radiators for our Čerenkov counters and had beams of ^{40}Ar at 1.88 GeV/nucleon and ^{56}Fe at 1.82 GeV/nucleon. For our latest run we had radiators of 3mm thick BK7W optical glass and 2mm thick fused silica. The effect of the upgrade was to increase the charge resolution from $\sigma_z = 0.25e$ to $\sigma_z = 0.18e$.

For this second run we used a beam of ^{40}Ca at 2.1 GeV/nucleon and analyzed data for 8×10^5 primary interactions. The results of the mean-free-path (MFP) analysis for fragment charges 10 to 18 and the beam are displayed in Fig. 1. The MFP of the primary beam, ^{40}Ca is shown in the upper left corner. One sees that it is quite constant with distance and it has the value of $8.01 \pm 0.04 \text{ cm}$. The other MFPs shown in Fig. 1 are for the secondary charges indicated and it is apparent that there is no systematic dependence other than being constant with distance from the primary interaction point, x . The values of

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the $\langle \lambda_Z^* \rangle_{(x > 3\text{cm})}$ for these charges are listed in Table I.

The Λ^* values are commonly calculated by normalizing the λ_Z^* values by a power law dependence, $\lambda \approx Z^{-b}$, rather than to the measured individual MFPs as we have done.

Table I. Mean Free Paths for $x > 3\text{cm}$.

charge	$\langle \lambda_Z^* \rangle_{(x > 3\text{cm})}$	$\chi^{2a)}$
20 ^{b)}	8.01 ± 0.04	43
18	8.46 ± 0.07	36
17	8.75 ± 0.10	20
16	9.18 ± 0.09	31
15	9.63 ± 0.12	14
14	9.90 ± 0.10	7
13	10.01 ± 0.13	30
12	10.45 ± 0.12	42
11	10.64 ± 0.16	24
10	10.58 ± 0.15	30

a) for 23 degrees of freedom

b) primary beam.

The final result of our analysis is shown in Fig. 2. Just as one saw with the individual charge MFPs, one sees in the global summation that there is nothing anomalous in the reactions we investigated. The x bin width in this plot is 3mm and the first bin is the 6 to 9mm bin. The data in this figure are fit well by a horizontal line with $\chi^2=30$ for 31 degrees of freedom. The curves drawn show what would be the effect of previously reported^{2,3}

This experiment has confirmed our previous result, now with higher quality detectors and a different target material, that large projectile fragments of high energy heavy ions exhibit normal mean-free-paths for reactions with $\Delta Z > 1$ at distances greater than 6mm from the primary interaction point. The charge range for each beam we used is listed in Table II. If anomalous exist they necessarily must have low velocity or low charge or be produced at large angles or result in $\Delta Z \leq 1$ reactions.

Footnotes and References

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Table II. Range of Covered Parameters	
parameter	range
production angles	$< 3^\circ$
distance	$> 6\text{mm}$
for secondary charges	13–24 from ^{56}Fe 11–16 from ^{40}Ar 10–18 from ^{40}Ca
reactions with	$\Delta Z > 1$

Fig. 1. Mean free path vs length of track. Horizontal scale is track length and vertical scale is the computed mean free path, both in cm. The vertical scale in each box ranges from 5 to 15 cm. The data points are for bins 3mm wide. The first bin for the primary beam is 15 to 18 mm. The first bin for the secondary fragments is 6 to 9 mm. XBL 8511-4561

Fig. 2. The charge-averaged secondary MFP vs. track length. The bins are 3mm wide and the first bin is for 6 to 9 mm. The curves show the effect of the anomalon results from refs. 2 and 3.

XBL 8511-4562

Implications of New Measurements of $^{16}\text{O} + \text{p} \rightarrow ^{12,13}\text{C}, ^{14,15}\text{N}$ for the Abundances of C,N Isotopes at the Cosmic Ray Source^{*,†}

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Introduction

The interpretation of cosmic ray measurements in terms of the source abundances and the propagation conditions requires accurate nuclear physics parameters. The current cosmic ray data is, in many cases, better than our ability to interpret it. In particular, the interpretation of the isotopic abundances of carbon and nitrogen, as a function of energy, requires nuclear excitation functions for masses 13, 14 and 15, and we report here preliminary results from an experiment designed to study the fragmentation of ^{16}O at intermediate energy.

The Bevalac Experiment

Fig. 1 shows the experimental arrangement at the LBL Bevalac. The ^{16}O beam, incident from the right, passed through monitors S1 and S2, focusing and bending magnets, and steering scintillators (E, W, U, D) upstream of the target, located in a vacuum tank. Fragments from interactions in the targets ($\sim 1 \text{ g/cm}^2 \text{ C}$ and CH_2) were measured ~ 7 meters downstream in the cave with a solid state detector telescope (Scope) which was movable in order to study the angular distribution of the fragments. The Scope consisted of three x-y planes of position-sensitive detectors and a stack of Li-drifted silicon detectors. The ΔE -E technique was employed to measure the mass of each particle stopping in the telescope.

Six angular positions from 0° to 2.75° were studied and the cross sections were obtained by integrating under the normalized angular distributions after correction for background, beam effects, and interactions in the detector stack. Hydrogen target cross sections were obtained by CH_2 -C subtraction. The isotopes of B, C, N and O have been analyzed to date, and here we focus on the $A = 13, 14, 15$ isobars for which the cross sections in hydrogen are shown

Fig. 1. Diagram of the B40 experimental area at the LBL Bevalac configured for this experiment.

XBL 8510-4378

in Table I compared to the predictions of the semi empirical formulae.¹ Fig. 2 shows the results of this experiment compared to previous data and to various excitation functions: solid curves – semi empirical formulae; dashed curves – scaled from ^{12}C measurements; dot-dash curves – “limiting” cases.^{2,3}

The Astrophysical Interpretation

Cosmic ray isotopic measurements of nitrogen are presently available at both low and high energy. In the latter case, the results at the cosmic ray source give $(^{14}\text{N}/\text{O})_s = 5\text{--}10\%$ with no ^{15}N required.^{2,3} At low energy ($\sim 150 \text{ MeV/nucleon}$), there are several reported isotopic measurements^{3–5} whose interpretation depends upon the adopted nuclear excitation functions. Isotopic measurements of $^{13}\text{C}/\text{C}$ ^{4,6} when interpreted in terms of a source ratio, $(^{13}\text{C}/\text{C})_s$, can be compared to $^{13}\text{C}/\text{C}$ measured in different regions of the galaxy.⁷

Conclusions

Using new cross section data, measured at the Bevalac, for the fragmentation of ^{16}O at intermediate energies, galactic propagation calculations can repro-

duce the measured $^{13}\text{C}/\text{C}$ data with a source component ($^{14}\text{N}/\text{O})_S = 3\text{-}6\%$ and no ^{15}N in the cosmic ray source. However, additional nuclear physics measurements are needed to fully specify the excitation functions and to explain, completely, the existing cosmic ray data.

Footnotes and References

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Fig. 2. Nuclear Excitation functions for the production of the A = 13, 14, 15 isobars (after decay) from ^{16}O fragmentation in a hydrogen target. Three predicted excitation functions are shown for comparison (see text for details). XBL 8510-4380

Table I.		
	This Work	Predicted
A=13:	24 ± 2 mb	23.9 mb
A=14:	40 ± 4 mb	50.4 mb
^{15}N :	27 ± 2 mb	24.6 mb
^{15}O :	50 ± 20 mb	34.2 mb

Range-Energy Relation for Heavy Ion Inertial Fusion

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The objective of Bevalac experiment #730H is to obtain the range-energy relation for low charge state beams of Au ions at energies $E/A \leq 150$ MeV in representative light (CH) and heavy (Au) materials. The experiment addresses problems pertinent to low-charge state beams envisioned for Heavy Ion Fusion (HIF). When such beams penetrate target materials, they will have charges far from their equilibrium values characteristic of their velocity and the target material. As a result the rate of energy loss dE/dx of the ions will be low initially, increasing rapidly as the valence and outer-shell electrons are stripped from the ions as they approach charge equilibration. Because of the suppressed values of dE/dx for the ions upon penetrating matter, the ranges of the ions in a given material will be dependent not only on their atomic number mass and velocity, but also on the charge state of the incident ion. An important aspect of Exp #730H is the availability of low-charge-state, high-rigidity beams of heavy nuclei at the Bevalac, where we have utilized Au beams accelerated and extracted at $Z_{\text{accel}} = 61, 35$ and 11.

The first phase of the experiment was carried out with Au^{+61} beams at $E/A = 150$ and 50 MeV to obtain the ranges and rates of energy low rates of Au in high- and low-Z materials under charge-equilibrated conditions. Fig. 1 gives the results of our range measurements of Au in CH and Au absorbers, obtained by time-of-flight, integral and differential range measurement techniques. The ranges of the Au ions were measured in the energy interval $22 \leq 152$ MeV using the 152 MeV/nucleon beam (solid points) and in the interval $12 \leq E/A \leq 50$ MeV using the 50 MeV/nucleon beam (open circles). The R-E data, when fitted to a quadratic polynomial by least squares, exhibit standard deviations in range of $\sigma = 0.4\%$, dispersions that include all statistical errors attributable to the range and velocity measurements. Included in Fig. 1 are the calculated range-energy, relations based on the proton range-energy relation of

Barkas and Berger¹ and the heavy ion range data ($E/A \leq 10$ MeV) of Heckman, *et al.*²

During this report period we made measurements on the ranges and energy-loss rates of Au ions, with $Z_{\text{accel}} = +11$ and $+35$ at energies $10 \leq E/A \leq 50$ MeV, to investigate possible deviations from the R/E relation, Fig. 1, attributable to the low-charge state values of the incident Au ions. The acceleration and extraction of the Au^{+11} beam at 50 MeV/nucleon for this experiment required the Bevatron to accelerate the ions using the 3rd harmonic, with extraction at 12.2 kG, which was the first demonstration that the Bevatron could be operated in this mode of operation.

Fig. 1. Range-energy relation for Au ions in CH and Au absorbers. Solid and open circles are data from beam energies 152 and 50 MeV/nucleon, respectively. The curves are predicted ranges from refs. 1 and 2.

XBL 8510-4339

Fig. 2 presents all of our observations on the dependence of dE/dx for Au beams in a CH absorber having initial charge-states $Z_{\text{accel}}=61, 35$ and 11 in the energy range $40 \leq E/A \leq 50$ MeV. Denoted as dE/dx (equil) is the dE/dx measured for Au^{+61} ions that have been degraded in energy from 150 MeV/nucleon, thereby insuring charge equilibration. Compared with these data are our dE/dx measurements in CH for beams extracted from the Bevalac at 50 MeV/nucleon with $Z_{\text{accel}}=61, 35, 11$. These results give evidence that, for the lowest charge-state ions, dE/dx is depressed by a factor about $1/2$ relative to dE/dx (equil) after an energy loss $E_{\text{LOSS}} \approx 0.2$ MeV/nucleon has occurred, i.e., after the ions have penetrated about 1.3 mg/cm^2 CH (which includes the thickness of the first scintillator of the TOF system). The measured dE/dx values converge to the equilibrium values by the time the beams have undergone on $E_{\text{LOSS}} \approx 1$ MeV/nucleon, equivalent to a penetration distance of about 3.5 mg/cm^2 .

The data are compared with a theoretical estimate derived from the work of Bailey, *et al.*,³ who give dE/dx versus E_{LOSS} for neutral Au ions at 46 MeV/nucleon in a variety of materials, assuming ion-ion collisions. Although the data can only be compared qualitatively with theory, it is evident that our measurements argue for a shorter equilibration distance (time) than suggested by the theory.

Footnotes and References

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Fig. 2. Energy-loss rates for Au ions in CH for beams at $E/A=50$ MeV, having charge states $Z_{\text{accel}}=61, 35$ and 11 . The data denoted dE/dx (equil) is the observed energy loss rate for ions degraded from $E_{\text{beam}}=152$ MeV/nucleon (See Fig. 1).

XBL 8510-4341

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Electromagnetic Radiation and Electrons Produced by ^{238}U Beams at Inertial Fusion Energies

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One of the methods being considered for driving controlled inertial fusion is imploding a DT fuel pellet with heavy ion beamlets. Dennis Keefe¹ has reviewed the subject extensively. Current thinking involves use of very heavy ion beams, Hg, Pb, or U

at energies in the neighborhood of 50 MeV/nucleon. Bangerter² has published theoretical yield calculations for uranium beams on two kinds of targets: (1) a hollow shell of frozen DT surrounded by a light-element stopping material, in turn surrounded by an

outer shell of Pb and (2) a similar target but with a small sphere of DT in the center surrounded by a Pb shell. The latter, more complicated, target gives a theoretically greater yield as the central sphere of fuel begins the thermonuclear burn, which then spreads to the imploding shell of DT. An important design consideration for this, as for other possible drivers, such as protons or laser photons, is that the driver energy be deposited in the outer ablatable material, which drives a compression of the DT fuel along an adiabat. The frozen DT must be compressed ten-fold linearly, that is, compressed to a density 1000 times normal to give an effective burn. Preheating of the fuel before compression is undesirable. Thus, production of any secondary radiation extending beyond the heavy ion range and preheating the fuel is to be avoided. Bangerter pointed out a special concern with the more complex target of type (2). That is, he worried about the propagation of Pb x rays produced in the outermost shell into the inner Pb layer, causing it to expand before the main compression shock wave arrives.

Some of us earlier made Bevalac x ray production studies, and Anholt,³ in particular, has made careful analysis of the most critical concern of Bangerter.² That is, the greatest electromagnetic transfer of energy between the outer and inner Pb shells arises from Pb L x rays. Anholt's analysis shows that atomic theories can now provide an estimate for radiative preheating of inner shells of high gain Bangerter's type (2) targets.

The present experimental study was undertaken to provide more directly a measure of photon and electron radiation produced by uranium ions near inertial fusion energy impinging on their targets of comparable Z and thickness to fusion pellets. It affords also an overview of the atomic physics in this untouched region of energy and Z and may serve in the design of more fundamental targets.

The Bevalac was tuned to deliver a beam of 99 MeV/nucleon uranium. At the end of the beam line was a vacuum chamber into which absorber foils could be introduced to degrade the energy of the beam. The beam left the chamber through a 35 mg/cm² mylar window as shown in Fig. 1. The

Fig. 1. The apparatus used to measure x rays and electrons from a simulated fusion pellet.

XBL 857-3045

beam passed through 18 cm of air and was stopped in a plastic scintillator. The live scintillator simulated the low-Z stopping material of a fusion target and served as a beam monitor. Spectra were taken with a Ge(Li) detector at 30 and at 45 degrees with and without 993 mg/cm² Be absorber to distinguish between electrons and electromagnetic radiation. Some of the runs were made with a tantalum foil just ahead of the stopping scintillator. The tantalum was used to simulate the outer coating of heavy metal on a fusion pellet. The detector efficiency curve was calibrated with radioactive standards placed on the front face of the scintillator at the beam spot.

Fig. 2 shows the pure scintillator target spectra at 30° and 45° with respect to the full energy beam particles, using a 993 mg/cm² Be absorber before the Ge(Li) detector to absorb electrons. These spectra were produced by only 10⁶ beam particles each. A single full energy (91.7 MeV/nucleon) U ion in the 236 mg/cm² scintillator target creates hundreds of uranium L x rays. The nearly stripped (carbon-like) ions produced L x rays which are estimated by relative Hartree-Fock calculations to be about 10% more energetic than neutral atoms because of reduced electronic screening. The x ray energies are further increased at our forward angles by Doppler shift, and the peaks are Doppler broadened as the ions slow down. The heavy ion elastically scatters target electrons and produces numerous bremsstrahlung photons. With our detection efficiency of $\Omega E = 5 \times 10^{-4}$, the probability that two or more photons will

Fig. 2. x ray spectra from 91.7 MeV/nucleon U+CH (using the scintillator as the target) at 30° (top curve) and at 45° (bottom curve). A 993 mg/cm² Be absorber was used to absorb electrons. XBL 857-3048

strike the x ray detector is high and pileup or sum peaks are seen.

The Doppler-broadened and shifted U K_α and K_β peaks are seen on the right-hand side of the spectra in Fig. 2 for full energy beam particles. There are three principal peaks in the UL x ray spectrum, and the relative intensities are very different from those in neutral or slightly ionized uranium.

It is not practical to make a precise comparison of energies. Not only are the peaks Doppler shifted and broadened in the thick target, but the equilibrium charge state Z_{eff} of the uranium is continuously changing during the slowing down process which changes the inner-shell binding energies and hence the x ray energies. No peaks of statistical significance can be seen above the continuum for the L radiative electron capture (REC). The K REC energy is off scale, but it is not expected to be observable with the K shells essentially filled.

The exponentially falling continuum is mostly due to primary bremsstrahlung, photons emitted when electrons of the system are subjected to large acceleration in the field of the uranium nucleus.

Fig. 3 shows a photon spectrum at 45° and full energy but with a 185 mg/cm² Ta foil just ahead of the scintillator. The beam exits the Ta foil at 67 MeV/nucleon. In comparison with the 45° spectrum of Fig. 2 we note, of course, the sharp K_α and L_β peaks of Ta. The uranium L x ray multiplet looks different. The upper two peaks are better resolved, and the lowest peak is seen only as a shoulder. The self absorption of Ta L x rays within the tantalum is appreciable, so that the detected Ta x rays are mainly from a thin layer of the back of the Ta foil. At the beam energy of 67 MeV/nucleon we have less Doppler smearing than from the higher U beam energies and the Doppler increase in energy is less. The peaks around 29 keV are summing peaks of U L x rays. The several peaks at energies just above the Ta L_β are also summing peaks of Ta K and U L x rays. The summing peaks of two Ta K x rays fall in the region of the U K x rays, and this fact will introduce uncertainty in the intensity of these unresolved peaks.

Based on sum peak intensities, the x ray data in Fig. 3 (x rays at 45°) and the data taken at 30° both indicate that ~280 U L x rays and ~26 Ta K x rays are produced for each incident U projectile. About 300 bremsstrahlung photons were detected at 45° (Fig. 3) and about twice that value at 30° for each projectile.

By analyzing difference spectra (with and without a Be absorber) we have estimated the upper limit of electron production. For both 30° and 45° measurements the electron yields were <40 electrons/projectile with average energies of ≈30 keV.

It is beyond the scope of this paper to deal with quantitative comparisons with theoretical cross sections. Certain qualitative aspects should be noted. The cross section for a particular x ray group – K, L, M, etc. – should be near maximum when the projectile velocity matches the Bohr orbital velocity. The universal curve (of Garcia, Fortner and Kavanagh⁴) shows this feature. At lower velocities the vacancy production falls off because bound electrons can respond adiabatically, and at higher velocities the fall-off comes according to the Bethe-Bloch formula

as $\sim 1/v^2$ because the Coulomb force field acts for a shorter time.

At the Bohr orbital velocity for a given shell the next outer shell may be rather highly stripped, a factor that inhibits x ray emission. Certainly this consideration alters the intensity patterns of a given projectile x ray group relative to neutral atom values. That is, $K_{\alpha_i}/k_{\alpha_i}$ ratios for projectile x rays are larger than for neutral atoms. For uranium the K orbital velocity match comes near 210 MeV/nucleon ($= 931 \times E_K/511$). The L orbital velocity match comes near 40 MeV/nucleon.

If we use the 45° x ray data from Fig. 3 we can calculate the fraction of the beam energy converted to electromagnetic radiation in this experiment. inertial fusion targets. The total photon and electron energy ($h\nu \gtrsim 10$ keV) available is about 18 MeV, which is about 0.08% of the beam energy. Some of the radiation is nearly isotropic and some is forward peaked, the reabsorption depending on geometry and materials of the target. Furthermore, since Ta L x rays were below the energy cutoff of our Ge(Li) detector, they were not measured and thus are not included in the 18 MeV total energy above. The L x rays from the outer metal coating (Pb in most designs) make the major contribution to electromagnetic preheating of any high Z material in the core, so they need to be considered separately according to the analysis of ref. 3.

Bangerter (1982) estimates that if the preheat electromagnetic radiations are deposited uniformly over the fusion pellet, 0.10% of the total beam energy is acceptable.

Search for Stable Fractionally Charged Particles

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LBL is involved in a collaboration with San Francisco State University and UC Irvine to search for stable fractionally charged particles in high energy nuclear collisions. The first phase of the project,

Fig. 3. An x ray spectrum for 91.7 MeV/nucleon U + Ta-CH. Sum or pile-up peaks can be seen above both the uranium L x rays and the tantalum K x rays.
XBL 857-3044

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a search using a 1.9 GeV/nucleon iron beam at the Bevalac, has already been published.¹ This search found no fractionally charged particles in about 2.0×10^6 collisions.

While almost all physicists agree that quarks, which are fractionally charged, exist, only integer charged particles have been detected. A few papers have claimed observation of quarks, but the evidence presented has not been very convincing. There is no satisfactory explanation for the fact that free quarks are not observed in matter.

Our collaboration is searching for quarks or other fractionally charged particles using several novel techniques. We are using the highest energy nuclear beams available. The targets are made of high Z material, since there is the possibility that fractionally charged particles may become deconfined during creation of the quark-gluon plasma.² Since once a fractionally charged particle becomes deconfined, it remains stable unless it combines with another fractionally charged particle, we have chosen to search bulk matter. The matter is used to stop and then trap any fractionally charged object. The technique is sensitive to wide ranges of masses for these objects and over the complete phase space for their production. Because we are using bulk matter, the experiment can use the full intensity of any accelerator.

The detector that we use for measurement of the fractionally charged particles is very similar to the apparatus built by Millikan in his oil drop experiment. The major differences between these detectors are that drops of mercury are used and the measurement procedure is done automatically for our detector. The mercury apparatus has been built by our collaborators at San Francisco State University and is described in the thesis of Joyce.³

The second phase of this program has been performed at the world's highest energy fixed target machine, the Tevatron at Fermilab with an 800 GeV/c proton beam incident upon nuclear targets. In a first run, a total of about 10^{15} protons struck a series of lead and mercury targets. The four mercury targets were interspersed among the lead targets so that any quarks or other fractionally charged particles could be sampled at different stopping depths of the hadronic shower. The mercury was used to slow down and trap any fractional particles which were produced. So far a small sample of the mercury from the Fermilab exposure has been analyzed. The

results have shown that no fractionally charged particles have been produced in about 10^6 collisions. However, we can only analyze mercury samples of the order of milligrams out of the total amount of mercury, which is about 40 kilograms.

Our collaboration has chosen to obtain better sensitivity by distilling the mercury, which will be gently heated in a conventional mercury still. Because of their image charges, fractionally charged particles will be trapped and remain in the residue. After all the exposed mercury sample is processed, the residue will be analyzed in the mercury drop detector. The mercury still is now being constructed at LBL. It should be operational soon and the exposed mercury processed.

A second run, with an integrated proton intensity of 4.1×10^{13} , was completed at Fermilab in August of 1985. This run used four tanks of liquid nitrogen to stop any fractionally charged particles produced by the Tevatron beam. There were two electrically charged wires in each of the tanks to attract the fractionally charged particles. If a fractionally charged particle hit a wire it would be trapped in the thin gold layer deposited on the glass fiber. After the exposure the wire was moved through a small bead of mercury to dissolve the gold. The small beads of mercury will be analyzed shortly for fractional charges.

We are presently preparing for an experiment that has been approved to run during the heavy ion running at Brookhaven. A letter of intent has been submitted for a future experiment during the CERN heavy ion program in 1986-7.

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LAMPF E645: A Search for Neutrino Oscillations

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With the addition of K.T. Lesko to our group, we have become involved with a large collaboration in a search for neutrino oscillations. This experiment is designed to look for oscillations of the type $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. Muon-type antineutrinos are produced as a result of pion decay in the LAMPF beam dump. The appearance of $\bar{\nu}_e$'s in this $\bar{\nu}_\mu$ beam is searched for in an 18-ton detector system containing forty 3 meter $\times$ 3 meter planes of scintillation counters and proportional drift tubes. A signature of a $\bar{\nu}_e$ interaction in the detector would be the observation of the reaction $p + \bar{\nu}_e \rightarrow n + e^+$. In order to minimize the background counting rate, the detector is surrounded by passive shielding (lead, iron, and dirt) and an active shield of liquid scintillator viewed by 360 photomultiplier tubes. This 6 inch layer of scintillator provides active veto information over 4π steradians around the detector and records both pulse height and time histories in order to yield adequate veto in-

formation for stopping and passing background events. We are working closely with the Argonne group on this aspect of the experiment. We plan to begin taking data within the next six months and, in six months of running, should be sensitive to neutrino mass differences $\Delta m^2 \geq 5 \times 10^{-2} \text{ eV}^2$ and mixing angles satisfying $\sin^2(2\theta) \geq 10^{-3}$.

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High Energy Atomic Physics

Harvey Gould

The goal of this program is to understand atomic collisions of relativistic ions and to test quantum electrodynamics (QED) in very high Z atoms. These are new areas of research which involve physics that is not accessible at lower energies or with lower Z ions. Recent results include detailed measurements of cross sections for electron capture in to the K shell and higher shells of relativistic xenon (Z=54) and ionization of K shell electrons of relativistic xenon. These and earlier measurements in this program have led to an understanding of relativistic heavy ion atom collisions, which in many cases, is now more complete than for nonrelativistic

collisions. Present activities include a measurement of ionization of L- and M-shell electrons of relativistic uranium, multiple electron capture and ionization, and, as a test of the higher order terms in the QED self-energy, a measurement of the 2^3P_0 lifetime in helium-like uranium (Z=92). Future experiments will explore a new mechanism for electron capture: capture from electron-positron pairs produced by relativistic ion-atom collisions. Other experiments will examine relativistic heavy ion-electron collisions, and channeling and polarization of relativistic heavy ions. This work has a direct bearing on the design of relativistic heavy ion storage rings and colliders.

PART III: THEORY

Quark-Antiquark Binding Force in the Skyrme Model*

Aiichi Iwazaki

Recently, the Skyrme model¹ has received much attention as a model of hadrons without quarks. The model is described simply by meson fields, but it can yield baryons¹⁻³ as topological solitons. It has been recognized⁴ that the model gives reasonable values for quantities in hadron physics at low energies. Hence we may ask what the connection is between this model and QCD, and if we can find any relics of quarks in the model.

We have shown that both a linear potential and a Coulomb potential between a quark and an antiquark can be identified in the Skyrme model. The coefficients in the linear potential (ar) and the Coulomb potential ($-b/r$) are compared with those used phenomenologically in a potential for charmonium.

Numerically, the coefficients (a and b) in the potentials was obtained such as

$$a = 0.1 \text{ GeV}^2 \quad \text{and} \quad b = 0.31 \quad .$$

Phenomenologically, the following values had been used in the calculation of charmonium spectrum,

$$0.16 < a < 0.2 \text{ (GeV}^2\text{)} \quad \text{and} \quad 0.4 < b < 0.53$$

We thus found that the Skyrme model yields reasonable values for the quark-antiquark potential.

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Origin of Attractive Force of Gravitation*

Aiichi Iwazaki

We present a model of gravitation in which the gravitational coupling constant is determined dynamically. Notably, its sign is shown to become positive (gravity) in the expanding universe, although it is possible, in principle, for the constant to take a negative value (anti-gravity). Interesting features of the model are that chaotic inflation^{1,2} may occur in an early period of the universe and that small density perturbation³

$$\left(\frac{\delta \rho}{\rho} \leq 10^{-4} \right)$$

may be generated.

Our model of gravity is described by the Lagrangian,

$$\mathcal{L} = \left[-\lambda \phi R + 1/2 g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] \times \sqrt{-g} + \mathcal{L}_m \quad . \quad (1)$$

where R is the Ricci scalar curvature, and λ and v are dimensional constants whose signs may be taken to be positive (their signs can be chosen arbitrarily without affecting any physical quantities). $\mathcal{L}$ is a Lagrangian of matter, which is assumed not to include the scalar field ϕ . This scalar field describes the strength of the gravitational coupling and may take to be either positive or negative.

We have shown by assuming the Robertson Walker metric that the universe is driven to choose the gravity phase ($\phi > 0$) through its expansion, and passes through the period of the chaotic inflation.

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Microcanonical Formulation of Lattice Gauge Theories with Fermions*

Aiichi Iwazaki

This formulation had already been used¹ as a practical calculational method in lattice gauge theories and had yielded results which agreed well with Monte Carlo results. However, the validity of the formulation was superficial and obscure until we proved² for the case of scalar field theories the perturbative equivalence between the microcanonical and standard functional formulations.

We have shown that the microcanonical formulation of $SU(N_c)$ lattice gauge theories and theories with fermions is perturbatively equivalent to the standard functional formulation. Furthermore, we have shown that Schwinger Dyson equations of $U(N_c)$ lattice gauge theories can also be derived in the microcanonical formulation. Our results validate the use in microcanonical simulations of the stan-

dard scaling law between the small bare coupling constant and the lattice spacing.

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Supercooled States and Order of Phase Transitions in Microcanonical Simulations

A. Iwazaki and Y. Morikawa[†]

Recently, microcanonical simulations have been used as a powerful method for numerical calculations in lattice gauge theories. Notably, it provides a new method for the distinction of first order phase transitions from second (or higher) order phase tran-

sitions. These distinctions have been also made in Monte Carlo simulations, for example, by examining the continuity of the internal energy at a critical point. However, the discontinuity in first order phase transitions may be smoothed out by finite

volume effects. Hence, it is favorable to have a method of making a distinction, which works well even in a finite volume.

According to microcanonical simulations, we can find the internal energies of supercooled (or superheated) metastable states. Namely, for a system with sufficiently small volume, its internal energy $\langle S \rangle$ ($\langle \rangle$ implies an average over a microcanonical ensemble) becomes a multi-valued function of temperature β^{-1} beyond a critical point of a first order phase transition. One branch of the function corresponds to the energy of the supercooled (or superheated) state. This is because even beyond the critical point such metastable states cannot decay into a stable state; surface energies between the two phases prevent the decay of the metastable states in the system with a sufficiently small volume. The multi-valuedness of $\langle S \rangle$ is revealed by examining the so-called, S-shaped curve¹ in the $\langle S \rangle$ vs. β plane. On the other hand, the multi-valuedness of $\langle S \rangle$ is not expected around a critical point of second order. The reason is that the internal energy is smooth at this critical point.

We have proposed an improved method for the distinction of orders of phase transitions. We have found that the method can enhance the S-shaped behavior of the first order phase transition (see Fig.

1). Furthermore, using the method, we can measure the internal energy, etc., in many points of β while reducing the time required to perform the calculation.

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Fig. 1. $\langle S \rangle / N_p$ of U(1) gauge theory with mixed action. Curve A by our improved method, curve B quoted from ref. 1 and curve C by our improved method with different parameters. XBL 8510-4401

Convergence of Perturbation Series in the Microcanonical Formulation of Quantum Field Theories*

Aiichi Iwazaki

Recently the microcanonical quantization method¹ has received much attention as a means of performing numerical calculations. Notably, it has been used in lattice gauge theories. Since the method is quite new to particle physicists, it is important to examine in detail the basis of this quantum formulation.

As is well known, the perturbation series in the

standard formulations (Feynman's path integral or canonical quantization) is not convergent, even if we use an ultraviolet cutoff and a finite volume. Although the series in the standard perturbation expansion can be summed up in some cases with appropriate methods of summation (Borel summation, etc.), the final results may still depend on the methods used. Furthermore, so called non-perturbative effects cannot be recovered unambigu-

ously from the standard perturbation expansion.

We have shown that for a sufficiently small expansion parameter, the perturbation series converges in the microcanonical formulation of the scalar theory and of the gauge theories with an even total number of degrees of freedom. The convergence of the series is only guaranteed for a finite volume. However, if we are able to sum the series and make appropriate analytic continuation in the expansion

parameter of the result, we may construct, in principle, all the regularized Green's functions in the infinite volume limit.

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Soliton Matter and the Onset of Color Conductivity*

B. Banerjee,^{} N.K. Glendenning and V. Soni[‡]*

A great deal of interest has focused recently on solitons as representing non-perturbative solutions of QCD for baryons.¹ A number of authors have shown that at the 30% level, solitons resemble nucleons.² What we find particularly appealing in this development is that, having a Lagrangian that describes the internal structure of the nucleon (soliton), one can investigate interesting questions concerning how the internal structure changes when solitons are assembled to form dense matter, and how the properties of matter change correspondingly.

Several of the more interesting questions concern the quark behavior in normal and in dense matter, such as the anomalous muon scattering on nuclei as compared to nucleons (EMC effect),³ and the onset of deconfinement. For these purposes the Skyrmion,⁴ which has no quarks, is not interesting. Rather, we would like to have a soliton with quarks that are confined, but not through the mechanism of an impervious bag. In the absence of a known soliton solution possessing true confinement, we opt for a model in which the quarks are deeply bound. The hybrid soliton model fills this requirement.^{5,6}

In this paper we focus on the behavior of the quark eigenvalues in compressed matter. At the densities that we have in mind, it is not unreasonable to organize the solitons into a crystal lattice because of the short range repulsion. In fact the problem would

be exceedingly difficult to solve otherwise. For the soliton, we employ a hybrid model consisting of quarks that are coupled to a topological configuration of scalar and pi meson fields.^{5,6} Each soliton has a full Dirac sea of quarks and three that fill a deeply bound color degenerate valence orbital. As the density of matter is increased we find that the quark eigenvalues shift in response to their neighbors. The valence orbital of each soliton in the crystal contributes to a band of triply degenerate levels, and the band is therefore fully occupied. For low to moderate densities we may say that soliton matter is a color insulator. However, above a certain density the valence level rises in energy and the top of the band intersects the lowest eigenvalue of the continuum. At this density matter ceases to be a color insulator and becomes a color and electric semiconductor or conductor.

For soliton matter arranged as a crystal the hedgehog meson configurations are centered at lattice points, thus generating a periodic field in which the quarks move. Therefore, boundary conditions must be imposed on the solutions of the Dirac equation so that the quark spinors obey the Bloch theorem. We employ the Wigner-Seitz approximation, which replaces the actual problem by a spherically symmetric one and solves for the ground state of the band.

The eigenvalues for the 0^+ , 0^- quark levels are shown in Fig 1. The lower of these two belongs to the filled sea of quarks, and the other is the valence orbital. This orbital as would be expected from the Schrödinger theory, is lowered in energy from the isolated soliton eigenvalue over a certain range of crystal spacings, and then it rises due to the compression of the solitons by their neighbors. The lower eigenvalue is increased for all crystal spacings, which behavior can be traced to the small component of the Dirac spinor when the eigenvalue is close to $-m$.

The Wigner-Seitz approximation allows us to calculate the eigenvalue of the ground state of each band ($k=0$). We need to estimate the band width. In the Schrödinger theory this is done by calculating the expectation value of the Hamiltonian. One could do the same in the Dirac case (except that the square of the Dirac Hamiltonian would have to be calculated, since it is linear in momentum). Alternately, we are motivated by the tight binding approximation of solid state physics. We calculate the eigenvalue for isolated solitons, i.e., with exponentially decaying boundary condition. The band width is then estimated as twice the difference between this energy and that computed with the crystal boundary condition, because the band should be spread symmetrically about the unperturbed case. For the valence levels the Wigner-Seitz approximation locates the bottom of the band. However for the levels belonging to the sea, it locates the top of the band, just as the sea eigenvalues in the free case are $-\sqrt{m^2 + k^2}$.

The band structure is shown in Fig. 1 by the shaded areas and the solid lines are the Wigner-Seitz eigenvalues ($k=0$). Several points deserve comment. We see a lowering of the valence quark eigenvalue by about 16 MeV at a lattice spacing $2R = 2.45$ fm. For smaller spacing the level rises steeply and the top of the band intersects the continuum at a spacing of about 1 fm, which corresponds to a density of 7 times normal nuclear density ($.15/\text{fm}^3$). In this model at such a density, matter ceases to be a color insulator and becomes increasingly color conducting as the density is further increased.

Fig. 1. Eigenvalues of the valence (0^+) and sea (0^-) orbitals of quarks in soliton matter as a function of Wigner-Seitz cell radius, R . The band of levels that develops as the spacing decreases is shown by the shaded region. In the upper right corner, an enlargement of the region indicated is shown. The eigenvalue of a free soliton is indicated by the arrow.

XCG 8411-13425

The above behavior is suggestive of quark deconfinement, although in this model the quarks are not truly confined but only deeply bound in the isolated state. The wave functions of the sea and valence orbitals are shown for a typical lattice spacing in Fig. 2, illustrating their periodicity in the crystal. In Fig. 3 we compare the quark distribution in soliton matter of several densities, illustrating the increasing concentration at the cell boundary for increasing density. For the pion decay constant we employ the experimental value $f=93$ MeV, and a coupling constant $g=7.55$, which yields a soliton mass of 966 MeV.

During the course of this work another paper has been published which investigated Skyrmion matter in a crystal lattice approximation.⁷ This model, however, does not possess quarks. Nevertheless, as these authors point out, the asymptotic behavior of the equation of state is such that the energy density behaves like $n^{4/3}$, just as a relativistic

Fig. 2. Upper (F) and lower (G) components of the Dirac spinor are shown for the valence and sea orbitals for a cell radius of 0.6 fm. XCG 8411-13424

Fig. 3. Probability distribution for the valence quarks for several cell radii, illustrating the increasing concentration of the quarks at the cell boundary as the compression of soliton matter increases.

XCG 8411-13423

gas of fermions. This is also the behavior in the model studied here, since the quarks pass into the continuum states of dense matter. We point out however, that for the Skyrmion, this behavior is an artifact of the form chosen to stabilize the Skyrmion, namely a term of fourth order in derivatives and hence in $k \sim n^{1/3}$. This is the lowest order stabilizing term, and can be viewed as the first in a series, the last of which will dominate the momentum dependence of the equation of state at high density.

In summary, we have investigated the behavior of quarks in soliton matter, using the hybrid model consisting of a topological meson field and deeply bound quarks. To organize the calculation, we placed the solitons in a crystal lattice. At a certain critical density, the top of the valence quark band becomes degenerate with the Fermi sea, meaning that the quarks in those states are no longer bound to a lattice site. At still higher densities, additional levels of the band rise into the continuum, suggesting that color conductivity is a gradual function of compression.

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Neutron Stars are Giant Hypernuclei*

N.K. Glendenning

Neutron Stars are studied in the framework of a relativistically covariant field theory of interacting nucleons, hyperons and mesons, which is solved in the mean field theory. The theory is constrained to account for the four bulk properties of nuclear matter, the saturation binding and density, compressibility, and charge symmetry energy. In addition it gives a good account of the single particle properties of finite nuclei. The equation of state calculated here nowhere violates causality, as frequently is the case in theories of neutron stars based on the non-relativistic Breuckner-Bethe method for the many body problem. The possibility of a phase transition to the pion condensed phase is examined and it is shown that this phase would preempt the possibility of any other phase transition involving the condensation of heavier mesons carrying quantum numbers

incompatible with the normal ground state of nuclear matter. It is found that the cores of the heavier neutron stars are dominated by hyperons and that the total hyperon population is about 15–20%, depending on whether pions condense. The rho meson, which is the driving force to isospin symmetry, plays a strong role in determining the baryon populations, and the lepton populations are strongly suppressed in comparison with the standard scenarios for neutron stars. Charge neutrality of the star is achieved instead among oppositely charged heavy particles. A possible consequence of this for the active lifetime of pulsars is noted.

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The Liquid-gas Phase Transition in Nuclear Matter*

N.K. Glendenning, L.P. Csernai,[†] and J.I. Kapusta[†]

The equation of state of nuclear matter is calculated in a relativistic field theory of interacting nucleons and mesons. The model reproduces bulk nuclear properties as well as many single-particle properties of finite nuclei. It yields a first order phase transition between gas and liquid below normal nuclear density. The dynamics of expansion through

this phase transition is calculated in the limit of maximum and minimum dissipation.

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- * Work in progress

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Introduction to QCD Thermodynamics and Quark-Gluon Plasma Phenomenology*

M. Gyulassy

These lectures, given in the Erice summer study on Nucleus-Nucleus reactions, April 1985, are designed to introduce nuclear physicists to QCD thermodynamics. Section 2 provides an introduction to the physics of dense nuclear matter and the motivation for studying QCD. The cut and paste method used to guess what the equation of state of high energy density matter may look like is presented. Section 3 introduces basic field theoretical techniques to the beginners. Functional methods to compute the partition function are "derived". We show how Feynman rules naturally emerge from such methods. A brief introduction to Grassmann techniques leads us to appreciate fermion determinants. The special problem of quantizing gauge theories such as QCD is treated by introducing the Fadeev-Popov trick. Finally, the Feynman rules for computing thermodynamic quantities in QCD are summarized and the lowest order results presented. Section 4 deals with the topic of asymptotic freedom and its relevance at high temperatures and/or densities. Debye screening of color electric fields and the lack of screening of color magnetic fields is discussed. In particular, we show that the lack of per-

turbative color magnetic mass implies that QCD perturbation theory suffers from a terminal disease associated with uncontrolled infrared singularities. This leads us in section 5 to discuss nonperturbative methods of lattice gauge theory. The change of variables from gluon fields to link matrices is motivated. We introduce the weird and unfamiliar lattice world of Wilson actions, plaquettes, and Polyakov loops. The Metropolis Monte Carlo algorithm which allows for numerical computation of QCD thermodynamics is described. The tricky question of the relevance of lattice theory for continuum physics is then addressed. The elusive asymptotic scaling window is introduced. Finally, recent attempts to include quark degrees of freedom are noted. We conclude these lectures on QCD thermodynamics with a better understanding of just how little is really understood but also with a reinforced belief that the transition from the hadronic to quark worlds probably will end up pretty much as we expect on phenomenological grounds.

Footnotes and References

* Condensed from LBL-19941.

A New Sphaleron in the Weinberg-Salam Theory?*

F.R. Klinkhamer

The Weinberg-Salam model¹ is a relatively simple example of a field theory with non-Abelian gauge fields and the Higgs mechanism of spontaneous symmetry breaking. Still its non-linearity makes the theory highly non-trivial. A better understanding, or even a complete solution, of the Weinberg-Salam theory is all the more desirable since the theory appears to give an excellent description² of the electroweak interactions, at least up to energies of the order of 100 GeV. In this article we deal with the vacuum sector of the classical theory, knowledge

about which will be a necessary ingredient for our eventual understanding of the quantum theory.

In a previous article³ by N. Manton and the present author a close approximation was found to a static but unstable classical solution in the vacuum sector of the Weinberg-Salam theory without the fermionic fields of quarks and leptons. Because it was unstable we considered it inappropriate to call it a soliton and we proposed for this solution, and others of the same kind, the word "sphaleron," which is

derived from the Greek adjective for "ready to fall." In this article we look for a new sphaleron (S^*), which is expected to be more complicated (axisymmetric) and heavier than the first sphaleron (S) discussed in ref. 3, which was spherically symmetric and had a mass of the order 10 TeV.

First let us recall how the sphaleron S was discovered, or rediscovered rather, since we learned afterwards that it was found many years ago by Dashen, Hasslacher and Neveu.⁴ Inspired by work of Taubes⁵ in the $SU(2)$ Yang-Mills theory with *adjoint* Higgs, Manton⁶ constructed in the space of classical static configurations of the Weinberg-Salam theory, where the Higgs fields are in the fundamental representation, a non-contractible loop passing through the unique vacuum solution at zero energy. This non-contractible loop, parametrized by $\mu \in [0, \pi]$, contains information of the behavior of the fields at spatial infinity, which is covered by the standard spherical coordinates ϕ and θ . For a fixed value of μ this information is given by a $SU(2)$ matrix $U(\phi, \theta; \mu)$. The configurations of the non-contractible loop are at infinity pure gauge as described by the matrix U and are interpolated inwards by use of two radial functions, one each for the gauge and Higgs fields. The $U(\phi, \theta; \mu)$ of ref. 6 is a specific map from $S^1 \times S^2$ into $SU(2) \simeq S^3$ which can be deformed to the homotopically non-trivial map $S^3 \rightarrow S^3$ with winding number $n=1$. The argument⁵ of how this loop leads to a non-trivial solution of the field equations runs as follows. The energy of the configurations of the loop considered attains its maximum at $\mu=\pi/2$. Choosing the two radial functions appropriately it is possible to minimize that maximum energy. Morse theory arguments can be used to show that, because the loop in configuration space was non-contractible, the configuration obtained from this mini-max procedure is a saddle-point of the energy functional and thus a solution of the field equations. There is one possible loophole in this argument: the non-compactness and infinite dimensionality of the configuration manifold can make that the configuration approached by the mini-max procedure is rather trivial. An example of this was given in ref. 7 for the Skyrme model. The non-contractible loop of configurations

that was considered had the following structure: for $\mu=0$ the vacuum, for $\mu=\pi/2$ a Skyrmion-antiSkyrmion pair at a separation d and with a relative isospin rotation, and for $\mu=\pi$ the vacuum again. For this loop the mini-max procedure never reached a new solution; rather the distance d kept on increasing indefinitely, always reducing the $\mu=\pi/2$ energy a little. Luckily, the Weinberg-Salam theory did not use a similar way out and the mini-max procedure did reach a new solution, i.e. the sphaleron S , for details of which the reader is referred to ref. 3. Clearly the Weinberg-Salam theory is richer than the Skyrme model in that it possesses also gauge fields and it is precisely those extra degrees of freedom that allow for a solution. The situation is analogous to that of the 't Hooft-Polyakov magnetic monopole solution,⁸ where the $SU(2)$ gauge fields and the adjoint Higgs are subtly working together to give a solution.

Physically the role of the sphaleron S is the following. As argued by 't Hooft⁹ there are instanton-like configurations in the Weinberg-Salam theory, starting at Euclidean time $t=-\infty$ from the vacuum and ending at $t=+\infty$ at the vacuum again, be it in a different gauge. The sphaleron S is just the maximum energy configuration at $t=0$ or, in physical terms, it lies on the top of the energy barrier between the vacua. Our present knowledge³ of S allows us to extend 't Hooft's approximate treatment, which was valid for small values of the Higgs quartic coupling constant λ , to all values of λ . The instanton has a winding number $n=1$ and an approximate action $A(n=1) \approx 8\pi/g^2$, where g is the $SU(2)$ coupling constant. With the known³ sphaleron energy $E_S = e \cdot 4\pi v/g$, where $e=e(\lambda/g^2)$ is a number of order 1 and v is the Higgs vacuum expectation value, we can set $A(1)=E_S \Delta t$, which gives the timelike extent of the instanton $\Delta t \approx e^{-1} M_w^{-1}$, where $M_w = \frac{1}{2} gv$ is the mass of the W boson. We could also start from a configuration¹⁰ with $n>1$ instantons on top of each other, which would have an action $A(n) \approx nA(1) + \text{interaction terms}$. Assuming Δt not to change significantly, we are thus led to expect a tower of sphalerons with increasing energies. We expect them to be spherical-symmetric, just as the original sphaleron S of refs.

3 and 4. These other sphalerons could be found explicitly by doing the mini-max procedure for non-contractible loops with winding number $n > 1$. Of course, other configurations of multiinstantons may lead to even more sphalerons.

These other possible sphalerons are not terribly exciting. Rather we will search for a really different sphaleron (S^*). Its existence should be related to a non-contractible *sphere* in configuration space, which *a priori* is a possibility, since $\pi_4(SU(2)) = \mathbb{Z}_2$. If S^* exists, the cyclicity of this homotopy group perhaps implies that it is not directly related to the known instantons of the pure gauge theory. Anyway, first we have to establish the existence of such a solution S^* and see if it is really different.

We construct a non-contractible sphere in configuration space and obtain from it our tentative ansatz for S^* . This ansatz has to be of a quite complicated form in order to stand a chance of being correct; specifically it is axisymmetric and involves three functions. Then we calculate the equations of motion for this ansatz. The general equations are certainly simplified by our ansatz, but it is not clear if a solution exists to them, since there appear two constraint equations on the polar dependence of the ansatz functions. Only at large distances are we able to construct an approximate solution. Hence there are two possibilities: either the ansatz allows miraculously for a solution of the field equations over all space or the ansatz is relevant only asymptotically and the fields in the inner region are different. Still, the ansatz is useful to calculate for $\lambda/g^2=0$ an upper bound on the energy E_{S^*} of 2.2 E_S . Finally, we compare the two ansätze for S^* and S , and show that they are very similar. In fact, it looks as if S^* may correspond to two sphalerons S infinitely far apart, which would be rather disappointing and an example

of the loophole in the topological argument as discussed above. Still the other possibility remains open that S^* is a truly new axisymmetric solution with a single core and an energy certainly larger than E_S and perhaps close to $2E_S$.

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Confinement at Large- N^*

F.R. Klinkhamer

Quantum Chromodynamics (QCD) is presently believed to be the fundamental theory that underlies the observed strong interactions.¹ It is surprisingly simple to say what this theory is: a $SU(3)$ gauge theory with (anti-)quarks in the fundamental $(\bar{3})_3$ representation. Apart from the current masses of the quarks, which are quite negligible anyway for the up and down flavors, there are no free parameters in the theory. The gauge coupling constant g is dimensionally transmuted² to a mass scale and all the mass ratios of hadrons and glueballs can, in principle, be calculated. On the one hand this makes QCD a powerful theory, but on the other hand this makes it, short of a complete solution, difficult for us to understand what goes on, since we cannot study the response of the theory under variation of its parameters.

Already in 1974 't Hooft³ suggested that we could consider the number (N) of colors as such a free parameter and that in particular it might be worthwhile to study the limit $N \rightarrow \infty$, where the theory simplifies dramatically, only "planar" Feynman graphs contributing. The assumption was, of course, that variation with N is not too drastic a change and that the $N \rightarrow \infty$ limit exists. It turned out to be relatively easy to establish³ that planar QCD has many of the desired features of real QCD, such as the existence of infinitely many light and narrow meson resonances and an explanation of Zweig's rule. Baryons are thought to arise⁴ as solitons of the effective meson theory and their mass diverges as $N=1/(1/N)$ just as the 't Hooft-Polyakov magnetic monopole has a mass $\propto 1/\alpha$, where $\alpha \equiv g^2/4\pi$ is the expansion parameter. In fact, this provides the field theoretic underpinning of Skyrme's successful idea that the baryons are solitons of the effective Lagrangian of the pions.⁵ It seems that we can write symbolically

$$\text{"QCD"} = (1 + 1/N + 1/N^2 + \dots)_{N=3} \quad (1)$$

and that taking the leading term is quite good an approximation already. Perhaps the *raison d'être* of eq. (1) is that the starting point planar QCD is a better

defined theory, i.e. having a less divergent perturbation series,⁶ compared with the QCD "theory". Since confinement is thought to be largely a matter of the gauge fields, appropriately called gluons, it is reasonable to consider just the pure gauge theory with quarks acting as sources only and not as dynamical fields (quenched approximation). In this case the expansion parameter is $1/N^2$, so that the leading term alone in eq. (1) is an even better approximation. Henceforth we consider only the pure gauge theory.

The successful phenomenology of mesons and baryons from the large- N point of view depends on one crucial assumption: confinement. This is less trivial than one might think at first. It is possible to show⁷ that the two-string tensions for heavy quarks in the adjoint and fundamental representations of $SU(N)$ are related at $N=\infty$ by

$$(\sigma_A = 2 \sigma_F)_{N=\infty} \quad (2)$$

The popular confinement scheme with $Z(N)$ vortices,⁸ where $Z(N)$ is the discrete center of the $SU(N)$ gauge group, implies $\sigma_A=0$, since the adjoint representation is blind to $Z(N)$. Were this the true mechanism of confinement we would conclude from eq. (2) that the large- N limit of QCD loses confinement, $\sigma_F(N=\infty)=0$. We see that a study of large- N QCD may tell us something about the nature of the mechanism that operates confinement in the real world ($N=3$), assuming the mechanism to be basically the same for all $N \geq 3$. But the numerical simulations would be much more time consuming than the present simulations of the pure $SU(3)$ lattice gauge theory by a factor of order $(N^2-1)/8$, which is the ratio of the number of degrees of freedom. Surprisingly Eguchi and Kawai⁸ discovered a few years ago that when N is large the volume to be used can be much reduced, even to a single-point lattice. Let us compare¹⁰ then for a fixed large number N of colors the number of degrees of freedom (D and V are the dimensionality and volume of the space time lattice)

lattice: d.o.f. $\sim DN^2V$

single point model: d.o.f. $\sim (DN^2V_{\text{eff}})/V_{\text{eff}}$, (3)

where $V_{\text{eff}} \sim N^2$ is the effective volume mimicked by the reduced model. Compared to a lattice with volume $V=V_{\text{eff}}$ the reduced model gains a factor $V_{\text{eff}} \sim N^2$, which for calculations at $N \sim 100$ is substantial. This improvement makes simulations of large- N QCD feasible on present day CYBERs and CRAYs.

In the complete article we briefly review the reduced model with a twist to it^{10,11} and discuss the numerical results obtained from simulations of this model. The results indicate that there is indeed confinement in large- N QCD. Everything looks the same as at $N=3$. As mentioned above this has important implications for the nature of the mechanism of confinement which we discuss at some length in the full article.

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Quark and Gluon Pair Production in SU(N) Covariant Constant Fields*

M. Gyulassy and A. Iwazaki

Previous work on ultrarelativistic nuclear collisions^{1,2} concentrated on the final state evolution of the quark gluon plasma. We now address the initial conditions of the plasma formation through color neutralization. Our model of the initial state is that after multiple gluon exchange the projectile and target nuclei acquire a color charge via a random walk process in SU(N). The color fields created between those nuclei are however unstable with respect to $\bar{q}q$ and gg pair creation. Up to now only Abelian models were studied.³ In this work we generalize those results to SU(N) for both quark and gluon pair production, and consider semiclassical corrections to

the rates due to the interactions between the pair. The competition between quark-antiquark and gluon pair production in the color neutralization process is illustrated. Possible phenomenological consequences for ultra-relativistic nuclear collisions are considered.

The equations of motion for quarks and gluons are

$$(i\gamma^\mu D_\mu - m_f)\psi_f = 0 \quad , \quad (1)$$

$$\partial^\mu F_{\mu\nu} + ig[A^\mu, F_{\mu\nu}] = gJ_\nu \quad , \quad (2)$$

where $J_\nu = \sum_f \bar{\psi}_f \gamma_\nu t_a \psi_f t_a$ and f labels the quark flavors.

The covariant-constant field,⁴ which satisfies eq. (2) in the source free region is of the form

$$F_{\mu\nu} = \langle F_{\mu\nu} \rangle n_a t_a \quad (3)$$

where $\langle F_{\mu\nu} \rangle$ is independent of x_μ , and n_a is an N^2-1 dimensional color vector. The external A_μ field corresponding to eq. (3) is

$$\langle A_\mu \rangle = -\frac{1}{2} \langle F_{\mu\nu} \rangle x^\nu n_a t_a \quad .$$

Since $\langle A_\mu \rangle$ is Hermitian, there exists a unitary matrix, U , that diagonalizes it. Since $N \times N$ traceless diagonal matrices can be expanded in terms of the $N-1$ traceless diagonal matrices, h_i , representing the Cartan subgroup of $SU(N)$, it is convenient to expand A_μ in the Cartan-Weyl basis of $SU(N)$. That basis consists of $N-1$ Abelian generators, h_i , and the $N(N-1)$ non-Abelian generators, $\{e_{ij}, i, j = 1, \dots, N; i \neq j\}$, such that $[h_i, e_{jk}] = (\tilde{\eta}_{jk}) e_{jk}$ where $\tilde{\eta}_{ij} = \tilde{\epsilon}_i - \tilde{\epsilon}_j$ are the root vectors of $SU(N)$ as expressed in terms of the elementary weight vectors $\tilde{\epsilon}_i = (\tilde{h})_{ii} = ((h_1)_{ii}, \dots, (h_{N-1})_{ii})$.

In this basis, $\langle A_\mu \rangle$ can always be expressed in terms of $N-1$ Abelian components, $\tilde{H}^\mu = (H_1^\mu, \dots, H_{N-1}^\mu)$, as

$$\langle A^\mu \rangle = \sum_{i=1}^N U H_i^\mu h_i U^\dagger \equiv U \tilde{H}^\mu \cdot \tilde{h} U^\dagger \quad (4)$$

where $U \in SU(N)$ and $\tilde{h} \equiv (h_1, \dots, h_{N-1})$. We can then expand the gluon field around the external field as

$$A_\mu = \langle A_\mu \rangle + U B_\mu U^\dagger = U(\tilde{H}_\mu \cdot \tilde{h} + B_\mu) U^\dagger \quad (5)$$

where B_μ represents the quantum fluctuations around the external Abelian field, $\tilde{H}_\mu$.

The physical significance of $\tilde{\epsilon}_i$ can be seen from eq. (1) by considering the equation of motion for the transformed quark field, $\psi' \equiv U^\dagger \psi$. Eq. (1) then reduces to the set of equations

$$(\gamma_\mu (i\partial^\mu - g\tilde{\epsilon}_c \cdot \tilde{H}^\mu) - m_f) \psi'_c = O(B\psi') \quad (6)$$

We therefore see that in this (one loop) approximation, the equations for the N quarks (of each flavor) in the prime basis decouple and reduce to Abelian type equations where $\tilde{H}^\mu$ plays the role of an effective electromagnetic field that couples to quarks with effective "charges" $g\tilde{\epsilon}_c$. The pair creation rate per unit volume of ψ'_c quarks of flavor f is thus

$$w_{q_c} = w_1(g\tilde{\epsilon}_c \cdot \tilde{F}^{\mu\nu}; m_f) \quad (7)$$

where $\tilde{F}^{\mu\nu} = i\partial^\mu \tilde{H}^\nu - i\partial^\nu \tilde{H}^\mu$, and the elementary spin 1/2 rate is given by

$$w_1(\sigma, m) = \theta(\sigma) \frac{\sigma}{4\pi^2} \times \sum_{n=1}^{\infty} \frac{1}{n} \int \frac{dE^2}{m^2} \exp(-n\pi E^2/\sigma) \approx \theta(\sigma) \frac{\sigma^2}{4\pi^3} \zeta(2) \quad (8)$$

with $\theta(x) = 0(1)$ for $x < (>) 0$, $\zeta(2) = \pi^2/6$, and where the approximation holds for $\pi m_f^2/\sigma \ll 1$.

Turning next to gluons, the equations of motion for B^μ in the one loop approximation are obtained by linearizing eq. (2) in B^μ . Since $B^\mu \in SU(N)$, we can expand it in the Cartan-Weyl basis as

$$B^\mu \equiv B_a^\mu t_a = \tilde{C}^\mu \cdot \tilde{h} + \sum_{i \neq j=1}^N W_{ij}^\mu e_{ij} \quad (9)$$

Inserting (5) into eq. (2) and using the Cartan-Weyl expansion (9) for B^μ leads to the following equations of motion for the fluctuations $\tilde{C}^\mu$ and W_{mn}^μ in the (linearized) one loop approximation to

$$\partial_\mu (\partial^\mu \tilde{C}^\nu - \partial^\nu \tilde{C}^\mu) = 0 \quad (10)$$

and

$$(D_{mn})_\mu (D_{mn}^\mu W_{mn}^\nu - D_{mn}^\nu W_{mn}^\mu) - (W_{mn})_\mu [D_{mn}^\mu, D_{mn}^\nu] = 0 \quad (11)$$

where effective covariant derivative D_{mn}^μ is given by

$$D_{mn}^\mu = \partial^\mu + ig\tilde{\eta}_{mn} \cdot \tilde{H}^\mu \quad (12)$$

We therefore see that the Abelian fluctuations, C^μ , obey free field equations whereas the non-Abelian fluctuations, W_{mn}^μ obey *Abelian* vector field equations in the external field, $\tilde{H}^\mu$, with an anomalous magnetic moment coupling. Note that $[D_{mn}^\mu, D_{mn}^\nu] = ig\tilde{\eta}_{mn} \cdot \tilde{F}^{\mu\nu}$. Obviously these equations are decoupled in this approximation. The effective "charge" of the W_{mn}^μ gluon is given by $g\tilde{\eta}_{mn}$. Pair production in $SU(N)$ covariant constant fields is thus equivalent to $N(N-1)/2$ different $SU(2)$ problems. Therefore, the pair creation rate per unit volume of $W_{mn} W_{nm}$ gluon pairs can be calculated from the known¹ rate, $w_1(gF^{\mu\nu})$, of vector mesons for $SU(2)$ covariant constant fields as

$$w_{gmn} = w_1(g\tilde{\eta}_{mn} \cdot \tilde{F}^{\mu\nu}) \quad (13)$$

where $\tilde{F}^{\mu\nu}$ is the same external covariant constant

SU(N) field as in eq. (8) and the spin 1 rate is given by

$$w_1(\sigma) = \theta(\sigma) \frac{\sigma}{4\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} \times \int_0^{\infty} dp_{\perp}^2 \exp(-n\pi p_{\perp}^2/\sigma) = \frac{1}{2} w_1(\sigma;0) \quad (14)$$

With the above rates we are able to derive the color neutralization equation

$$\frac{d\langle \vec{Q}(t) \rangle}{dt} \approx -\frac{2^{3/2}}{\tau_1} \left[N_f \sum'_{\pm \vec{q}_i} \vec{q}_i (\vec{q}_i \cdot \langle \vec{Q} \rangle)^{3/2} + (1-2^{-3/2}) \sum'_{\vec{q}_0} \vec{q}_0 (\vec{q}_0 \cdot \langle \vec{Q} \rangle)^{3/2} \right] \quad (15)$$

where the sums are restricted to charges with $\vec{q} \cdot \vec{Q} > 0$.

Therefore for SU(3), we find the remarkable result that the vector nature of eq. (26) is irrelevant, and the solution is accurately given by the power law

$$\vec{Q}(t) = \vec{Q}_0 / (1 + t/\tau_{1/4}(Q_0))^2 \quad (16)$$

as in the Abelian case,[‡] but with the characteristic time required to neutralize 3/4 of the initial color

field given by

$$\tau_{1/4}(Q_0) = 0.36 \tau_1 Q_0^{-1/2} \quad (17)$$

These results have a number of interesting phenomenological consequences for ultrarelativistic nuclear collisions which discussed in this paper.

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New Matter in Heavy Ion Collisions*

F.R. Klinkhamer

An effective low energy Lagrangian should contain at least the pions and the ρ vector mesons. Many years ago Sakurai drew attention to properties (universality, vector dominance, current field identity) that point toward some kind of gauge invariance. Only recently was an effective Lagrangian proposed¹ that realizes Sakurai's idea. This Lagrangian was, of course, not really derived from QCD; rather it emerged from postulating appropriate collective variables. With these variables and the basic dynamics of the non-linear sigma model there is little freedom left, a single parameter a , in fact. For the value $a = 2$ several interesting relations follow. For this reason we think that this Lagrangian with $a = 2$ is an important part of the full effective theory of low energy mesons. It is then appropriate to look for classical solutions. Normally we would not be interested in classical solutions of a theory with $g^2/4\pi \approx 2.8$, which certainly does not look very small. But the underlying theory of QCD does have a "small"

parameter $1/N$, which translates² to f_π and g being of order $N^{1/2}$ and $N^{-1/2}$, respectively, so that the effective Lagrangian is proportional to N , which makes a saddle-point approximation reasonable.

We have studied two simple types of classical solutions, but there may be others,^{3,4} probably with higher energy. The first was basically the Skyrme⁵ soliton in the π -field, but now dressed with a hedgehog configuration of the ρ -field.⁶ This solution has baryon number $B = 1$ and energy $E \approx 1.1$ GeV. The second with $E \approx 1.5$ GeV was a static, but unstable, solution which excites only the ρ field and which we called the ρ -sphaleron. This solution lies on top of an energy barrier between the vacuum in different gauges, but the same physical vacuum all the same. In the Weinberg-Salam (W-S) theory the passage over this barrier induces a change in baryon number $\Delta B = 1$, and in fact the WS-sphaleron has $B = 1/2$.⁷ In the $\rho\pi$ -theory, where there is no anomaly for the baryon number current (left-right symmetry),

there is no such signal, and the ρ -sphaleron has baryon number 0. Still, if one would try to excite a field configuration close to that of a sphaleron one would stand a better chance for the $\rho\pi$ -theory. Not only are energies of 1 GeV more manageable than those of 10 TeV, but precisely the fact that $g^2/4\pi$ is not very small in the $\rho\pi$ context, whereas it is in the electroweak theory, is of practical importance. The size of a classical solution is in general proportional to $(4\pi/g^2)E^{-1}$, so that the ρ -sphaleron is not unreasonably large. In fact, the sphaleron radii are approximately ⁷

$$R_{\text{Sph}}^{(\rho)} \approx R_{\text{Sk}}^{(\rho\pi)} \approx 2 m_\rho^{-1} \approx 0.5 \text{ fm}$$

$$R_{\text{Sph}}^{(\text{WS})} \approx 2 m_W^{-1} \gg 1/E_{\text{Sph}}^{(\text{WS})} .$$

Twice these values give the size of the region over which the field should be coherent. For this reason the experimental study of configuration space seems more feasible in relativistic heavy ion collisions. The size and average energy density of the $\rho\pi$ -Skyrmion or ρ -sphaleron gives an estimate of the required performance of these experiments: *an energy density of 2 or 3 GeV fm⁻³ deposited in a volume of some 1 fm³*. Note that these energy densities are less than the estimated density where chiral symmetry would be restored, which would invalidate the effective theory used here. These experiments would permit a study of the structure of configuration space of the $B = 1$ sector far away from the usual form of matter (i.e. the nucleon in guise of a $\rho\pi$ -Skyrmion) where there may be a new solution (Sk*, see Section 5 of the complete article), or in the $B = 0$ sector the structure as determined by the unstable ρ -sphaleron solution and others of this type.⁴ For the moment we have not thought much about possible signals. In

ref. 8 it was shown that fermions coupled covariantly to the ρ , i.e. in the Lagrangian a term $\bar{\psi}(\gamma^\mu D_\mu + m)\psi$ has a large cross section with the ρ -sphaleron. But what are these fermions if we take the view that the nucleons are not elementary, but solitons rather of the π and ρ fields? At the very least, such a Lagrangian term for nucleons must be changed by the effect of a form factor. Another characteristic of the ρ -sphaleron may be its classical magnetic dipole moment.⁷ Also in a heavy ion collision the decay of fields excited near the Sk* (asymptotic) solution can take a rather long time. Anyway, it is clear that heavy ion collision experiments can give us a glimpse of configuration space far away from the standard form of matter.

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Space-Time Development of Nuclear Stopping*

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From the pA data we could deduce how much energy is lost by the leading baryon *after* traversing a certain thickness of nuclear matter. Our analysis

confirmed earlier estimates that about 90% of the incident energy of a proton could be lost after traversing 14 Fm of nuclear matter. However, until now

the question of *where* that energy is deposited has not been seriously addressed. Obviously the data provide constraints only on the momentum space aspects of models, which in our case is the value of $\alpha = 3$. The space-time development of stopping and energy deposition is largely unconstrained by the available data. However, for applications to nuclear collisions it is necessary to know not only how much energy is lost but also where that energy is deposited.

We have therefore extended our previous studies by developing a Monte Carlo program to explore the consequences of different assumptions about the space time evolution of stopping.

The basic input quantity is the energy deposition per unit length. For an interaction at point z_0 , the energy deposited at z in the form of on shell secondaries is

$$\frac{dE^x}{dz} = \int dy P_f(z-z_0; y) m_{\perp} \cosh(y) \frac{dN}{dy} \quad (1)$$

where dN/dy is the final rapidity density of secondaries. Since the empirical dN/dy is only a slowly varying function of y in the central region, we see that longitudinal growth implies that dE^x/dz is approximately a constant given by $\sigma \sim 1 \frac{\text{GeV}}{\text{fm}}$. The energy deposition per unit length can be approximately constant, of course, only over a finite range. That range is fixed simply by energy conservation. For a target chain carrying an energy fraction x , energy conservation fixes its "length" $\ell(x)$ to be

$$\ell(x) = xE_0/\sigma \quad (2)$$

where E_0 is the incident energy. At the point where the string is stretched to length $\ell(x)$ all the kinetic energy of the leading parton has been converted into potential energy. That potential energy is in turn converted via the Schwinger mechanism into energy of pairs that are formed in the color neutralization process. A target chain formed at depth z_0 therefore leads to an approximately constant energy deposition per unit length over a finite range $z_0 < z < z_0 + \ell(x)$, so that

$$\frac{dE^x}{dz} \approx \sigma \theta(z-z_0) \theta(z_0 + \ell(x) - z) \quad (3)$$

Summing over all target chains leads then to the estimate

$$\frac{dE^x}{dz} \approx \sigma \left\langle \sum_i \theta(z-z_i) \theta(z_0 + \ell(x_i) - z) \right\rangle \quad (4)$$

where the average denoted by $\langle \dots \rangle$ is over the multiplicity of target chains, their production points z_i , and their energy fractions x_i .

What we must next specify is the distribution of $z_0, \dots, z_N$ and $x_1, \dots, x_N$ as well as of N . The distribution over N is given by a Poisson from Glauber theory, such that $\langle N \rangle = 2R/\lambda$, where $2R$ is the thickness of nuclear matter. The distribution of the fractional energies, $x_1, \dots, x_N$, carried by the N target chains is completely specified in our model as

$$D_N(x_1, \dots, x_N) = \frac{K(1-x_1)}{1} \frac{K(1-x_2/(1-x_1))}{(1-x_1)} \dots \quad (5)$$

This distribution leads to the average fractional energies, $\bar{x}_i = \alpha^{i-1}/(1+\alpha)^i$, for the target chains.

The distribution of interaction points, z_i , on the other hand, is not specified by the model as formulated in momentum space. To estimate the energy deposition we consider two extreme models for the distribution of production points, z_i . The first model for that distribution follows naturally from multiple collision theory:

$$S_N(z_1, \dots, z_N; 2R) = \frac{N!}{(2R)^N} \theta(z_2 - z_1) \dots \theta(z_N - z_{N-1}) \quad (6)$$

where $2R$ is the thickness of the nuclear slab and $0 < z_i < 2R$ for all i . With eq.(6) the average production point of chain i is $\langle z_i \rangle = 2Ri/(N+1)$.

A second possibility for the distribution of interaction points is suggested by the parton model. In that model partons are assumed to have very large mean free paths. It is only because there are so many of them that a few can nevertheless interact inside a finite nucleus. In that picture the z_i are thus uniformly distributed over the nuclear thickness. Such a distribution thus corresponds to

$$S_N(z_1, \dots, z_N; 2R) = (2R)^{-N} \quad (7)$$

On the average, there is an interaction every $2R/(N+1)$ as with the time ordered distribution (6). However, with (7) there is no correlation between the interaction point and the energy of the chain.

To study the effects of fluctuations in the number of chains, their energy fractions, and production points we have written a Monte Carlo program to evaluate the ensemble average in eq.(4), sampling the number of chains from a Poisson, the x_i from the distribution (5), and z_i from either (6) or (7). We have also included the contribution from the projectile chain assuming $z_0=z_1$ in (4). The results of such calculations are given in Table I. In that table the average energy loss and deposition in nuclear matter of thickness 14 Fm is given as a function of incident energy, E_0 . (Units are in GeV.) Cases $\alpha=1$ and 3 are again considered. The upper and lower estimates for the energy deposition are obtained using (6) or (7), respectively. Note that while the energy loss is greater for $\alpha=1$, the energy deposition is smaller in that case because the chains are longer. Note also the saturation of the energy deposition above $E_0>50$ GeV. The most remarkable point is the relative insensitivity of the total energy deposition to variations in α and the distribution of the z_i . The maximum average energy deposition in 14 Fm of nuclear

matter is thus $\sim 30 \pm 10$ GeV.

These results imply that energy densities in excess of one order of magnitude above the ground state value should be easily accessible in central collisions of heavy nuclei at energies $KE_{cm} \approx 3 \pm 1$ GeV/nucleon ($KE_{lab} \sim 17-50$ GeV/nucleon). The unique feature at these energies is that the baryon density reaches the maximum value that could ever be attained in a laboratory via nuclear collisions.

Table I: Average energy loss and deposition

E_0	30	50	100	
$\alpha = 3$	E_{loss}	24	40	80
	E_{dep}	22-26	29-33	38-42
$\alpha = 1$	E_{loss}	27	47	95
	E_{dep}	16-22	20-26	25-31

Footnotes and References

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Pion Interferometry of the Inside Outside Cascade

M. Gyulassy and K. Kolehmainen

One of the basic phenomena in high energy hadronic collisions is the inside outside cascade. Due to Lorentz time dilation¹ the production of a particle rapidity, y , cannot be localized to within $\Delta z \sim \tau_0 \sinh(y)$, where $\tau_0 \sim 1$ fm/c. This means that the momentum and the production point are strongly correlated. Pion interferometry² is traditionally used to measure the space time structure of reactions. However, the conventional results only follow in the absence of space- momentum correlations. In ref. 3 it was shown that such correlations could alter significantly the interference patterns. However, the Wigner function approximations used in that study lead to Lorentz noncovariant expressions. Therefore, we employed the general current ensemble formalism developed in ref. 2 to investigate this question. In particular our goal was to find out exactly how $\pi^+\pi^-$ correlation measurements could be used

to verify this basic phenomenon.

We start by considering an ensemble of currents with Fourier transform

$$j(k) = \sum_{i=1}^N e^{i\phi_i} e^{ikx_i} j_0(y-y_i, k_\perp) \quad (1)$$

where y_i is the longitudinal rapidity of source i in a frame where $k^\mu = (m_\perp \cosh y, \vec{k}_\perp, m_\perp \sinh y)$. Source i is characterized by a current $j_0(x)$ is centered initially at space-time point x_i . We further assume that the phases ϕ_i of the different sources is random.² The ensemble is specified by the probability $D(x_0, y_0)$ for finding a source with rapidity y_0 at x_0 . The single pion inclusive distribution is then

$$P_1(k) = \langle j(k)^2 \rangle =$$

$$\langle N \rangle \int dy_0 D(q=0, y_0) j_0(y-y_0, k_\perp)^2 \quad (2)$$

where $D(q, y_0)$ denotes the Fourier transform of D in

x. The correlation function is given by

$$C(k_1, k_2) = \frac{P_2(k_1, k_2)}{P_1(k_1)P_1(k_2)} = 1 + \frac{G(k_1, k_2)^2}{G(k_1, k_1)G(k_2, k_2)} \quad (3)$$

where

$$G(k_1, k_2) =$$

$$\int dy_0 D(k_1 - k_2, y_0) j_0^*(y_1 - y_0, k_{1\perp}) j_0(y_2 - y_0, k_{2\perp}) \quad (4)$$

We characterized the inside outside cascade model by

$$D(x, y) = D(\tau, \eta, y) = \frac{1}{\tau_0} \delta(\tau - \tau_0) \delta(\eta - y) \quad (5)$$

where $\tau = (t^2 - z^2)^{1/2}$ is the proper time, $\eta = \frac{1}{2} \ln(t - z)/(t + z)$ is the rapidity-like variable, and y is the particle rapidity. The parameter τ_0 characterizes the proper time at which interactions between the particles cease. The form of the source currents j_0 depends of course on the dynamics. From eq. (4) it is clear then that G depends not only on D but also on the dynamical details described by j_0 .

We considered a simple pseudo-thermal source function given by

$$j_0(y, k_\perp) = \exp\left(-\frac{m_\perp}{2T} \cosh(y)\right) \quad (6)$$

where the transverse mass and rapidity are related to $k_\perp$ by $m_\perp^2 = m^2 + k_\perp^2$. This parameterizes the sources in terms of an effective temperature T . The invariant single inclusive pion distribution with such a source is

$$P_1(k) = aK_0(m_\perp/T) \quad (7)$$

where q is a normalization constant. Thus T characterizes the average transverse momenta of the pions, which are uniformly distributed in rapidity. In this

model the correlation function depends on two parameters, τ_0 , and T . The function G is found to be

$$G(k_1, k_2) = K_0\left((m_1^2 + m_2^2)(1/(4T^2) - \tau_0^2) + 2m_1 m_2 [(2T)^{-2} + \tau_0^2] \cosh(y_1 - y_2) - i\tau_0/T(m_1^2 - m_2^2)^{1/2}\right) \quad (8)$$

with $Q^\mu = k_1^\mu + k_2^\mu$ and $q^\mu = k_1^\mu - k_2^\mu$. $K_0(z) \propto \int dt \exp(-z \cosh t)$ is the conventional modified Bessel function of a complex argument.

Obviously, the correlation function depends on three variables, the two transverse masses m_1, m_2 , and the rapidity difference $y_1 - y_2$. The structure of (8) is obviously rather different from conventional Gaussian or Kopylov parameterizations.² This means that a full three dimensional analysis of pion correlations is necessary to disentangle τ_0 from T . We have also verified that the usual procedure of plotting the correlation function as a function of one variable, for example $\vec{q}$ loses all information about the inside outside nature of the underlying dynamics.

Further consequences of these results and other aspects of interferometry involving space-momentum correlations are currently being written up.

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Correlated Nuclear Flow, Deuteron Production, and the Apparent Entropy in Nuclear Collisions*

M. Gyulassy, E. Remler, and K. Frankel

The problem of composite fragment production in high energy nuclear collisions has generated interest because of the so called entropy puzzle. De-

tailed calculations¹ of the high energy ($E \gtrsim 50$ MeV) differential yields of deuterons agree well with the data even for central collisions. However, calcula-

tion of the total yields is very difficult because corrections to the theory involving the whole space-time evolution of the system become important for low energy deuterons. At this time, such calculations have not even been attempted. Therefore, the entropy puzzle could be due to comparing theoretical calculations beyond their range of validity to data extrapolated from the actually measured domain.

In this work we show that a unique aspect of deuteron production is its sensitivity space-momentum correlations, $\langle x_i p_j \rangle \neq 0$. Only composite fragment yields provide information on such correlations which are associated with the interesting question of whether collective nuclear flow is actually generated in nuclear collisions. Such real phase space correlations have been ignored in previous analytic models which have been used to analyze composite data. We show that such correlations always tend to enhance the total deuteron yields. In addition, we study the connection of the total deuteron yields to the entropy. We derive the familiar entropy formula in a more general way (not involving equilibrium assumptions) which incorporates full six dimensional phase space correlations. This derivation emphasizes, however, that considerable theoretical ambiguity exists in the interpretation of the derived entropy from composite fragment abundances.

As shown in ref. 1 the distribution of primordial deuterons is related to a neutron-proton source distribution function, $S_f(\phi_n, \phi_p)$, via

$$\frac{d^3 N_{d'}}{d\mathbf{P}^3} = \frac{3}{4} \int d\phi_n d\phi_p \delta^3(\mathbf{p}_n + \mathbf{p}_p - \mathbf{P}) W_D(\phi) S_f(\phi_n, \phi_p) \quad (1)$$

To gain insight into how correlated nuclear flow could effect the deuteron yield, we consider a simple Gaussian parameterization of the source distribution given by

$$S_f(\phi_n, \phi_p) = N_n N_p f(\phi_n) f(\phi_p) \quad (2)$$

where

$$f(\phi) = F^{-1/2} \exp\left(-\frac{1}{2} \phi^T F^{-1} \phi\right) \quad (3)$$

with $\phi^T F^{-1} \phi = \sum_{ij} \phi_i F_{ij}^{-1} \phi_j$, $\phi = (x_1, x_2, x_3, p_1, p_2, p_3)$,

and $F \equiv \det(F)$. Although this neglects two body correlations, it allows us to study analytically the effects of non spherical spatial shapes, a nontrivial momentum flow matrix, in addition to space-momentum correlations.

The average phase space moments, $\langle \phi_i \phi_j \rangle$, corresponding to $f(\phi)$ are related to the generalized phase space flow matrix F via

$$\langle \phi_i \phi_j \rangle = F_{ij} \equiv \begin{pmatrix} F_x & C \\ C^T & F_p \end{pmatrix}_{ij} \quad (4)$$

Therefore, $(F_x)_{ij} = \langle x_i x_j \rangle$ specifies the spatial shape of the source, $(F_p)_{ij} = \langle p_i p_j \rangle$ specifies the momentum space shape, and $C_{ij} = \langle x_i p_j \rangle$ specifies space-momentum correlations.

The distribution of primordial participant protons is related to $f(\phi)$ via

$$\frac{d^3 N_p}{d\mathbf{P}^3} = N_p \int \frac{d^3 \mathbf{x}}{(2\pi)^3} f(\phi) = \frac{N_{p'}}{(2\pi)^{3/2}} F_p^{-1/2} \exp\left(-\frac{1}{2} \mathbf{p}^T F_p^{-1} \mathbf{p}\right) \quad (5)$$

This shows that F_p is the usual sphericity or momentum space flow matrix that can be measured by exclusive momentum analysis.

As in ref. 1 we approximate the deuteron Wigner density also by a Gaussian:

$$W_D(\phi) = D^{-1/2} \exp\left(-\frac{1}{2} \phi^T D^{-1} \phi\right) \quad (6)$$

where D^{-1} is a diagonal matrix with elements $D_{ii}^{-1} = 1/d_x^2$ for $i=1,2,3$ and $D_{ii}^{-1} = d_p^2$ for $i=4,5,6$. Fitting the average deuteron moments, $\langle \phi_i \phi_j \rangle$ to those obtained from realistic wavefunction, we find that $d_x = 2.24$ Fm and $d_p = 2.33$ Fm. This leads to

$$\frac{d^3 N_{d'}}{d\mathbf{P}^3} = \frac{N_{d'}}{(2\pi)^{3/2}} \frac{1}{2} F_p^{-1/2} \exp\left(-\frac{1}{4} \mathbf{P}^T F_p^{-1} \mathbf{P}\right) \quad (7)$$

where the total number of primordial deuterons is given by

$$N_{d'} = \frac{3}{4} N_n N_p F + D_r^{-1/2} \quad (8)$$

and where $D_r = RDR = \text{diag}(d_x^2/2, 2/d_p^2)$. Eqs.(7,8) are the basic results.

In the limit when F_x, F_p , and C can be approximated by diagonal (3×3) matrices, (8) reduces to a simple form that immediately reveals the effect of correlated nuclear flow on the total primordial deuteron yield:

$$N_d = \frac{3}{4} N_n N_p (F_\lambda + \frac{1}{2} d_\lambda^2)(F_p + 2d_p^2) - C^2 \quad (9)$$

Obviously, phase space correlations ($C \neq 0$) tend to enhance the deuteron yields, while the finite deuteron sizes $d_\lambda \approx d_p \approx 2.2$ Fm tend to reduce that yield. These and further results are currently being written

up.

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Cross Sections of High Energy Nuclear Reactions*,†

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Introduction

It is well known that high energy elastic scattering of hadrons on nuclei (h-A) can be accounted for by geometrical models such as the Glauber theory¹ and the Chou-Yang model.² Consequently, the *reaction* cross section may be computed by means of these models. In this paper, we propose to use simple formulae derived from the optical model (OM) to analyze reaction cross sections.

The formula for the h-A reaction cross section has the same A dependence as expected from the rms radius of the Fermi distribution of nuclear matter. The appealing feature of our formula is its simplicity. This is shown by the analysis of high energy nuclear data of p, $\pi^\pm$, $K^\pm$ and $\bar{p}$ reactions from Serpukhov.³ Our approach is further extended to heavy ion (HI) reactions. The cross section thus obtained resembles that of p-A, and predicts the well known behavior of the overlapping parameter of the Bradt-Peters formula. We mention that our OM approach enables us to relate the HI cross section to that of p-A by a simple expression.

Derivation of Nuclear Cross-Sections

We begin with the hadron-nucleus reaction, denoted by $\sigma_h(A)$, A being the mass number of the target nucleus of radius R. According to the optical model⁴, the absorption cross section is given by

$$\sigma_{abs} = \pi R^2 \int_{0 \leq b \leq R} (1 - e^{-2x/\lambda}) \frac{db^2}{R^2} \quad (1)$$

where b is the impact parameter, $2x = 2 \sqrt{R^2 - b^2}$ the traversal and λ the mfp of absorption (See Fig. 1a). We now assume the large A approximation and get

$$\sigma_h(A) = \pi r^2 \left(A^{1/3} - \frac{a}{A^{1/3}} \right)^2 \quad (2)$$

where

$$a \equiv (\lambda/2r)^2 \quad (3)$$

We note that the A dependence of this cross section turns out to be the same as that of the rms radius of the Fermi distribution, indicating that our approach amounts to using the Fermi distribution to estimate the parameters r and λ from the reaction cross section.

For the heavy ion reaction we proceed in the same way. First, consider the case of like nuclei and let $R_1 = R_2 \equiv R$ be the radius and a the distance between the centers (Fig. 1b). Then eq. (1) becomes

$$\sigma = 2\pi R^2 \int_{2R} \frac{da^2}{R^2} \int_R (1 - e^{-2x/\lambda}) \frac{db^2}{R^2} \quad (4)$$

For unlike nuclei, $R_1 \neq R_2$, we assume the following substitution

$$2R \rightarrow R_1 + R_2$$

and large A approximation to obtain

$$\sigma(A_1, A_2) = \pi r^2 \left(A_1^{1/3} + A_2^{1/3} - \frac{c}{A_1^{1/3} + A_2^{1/3}} \right)^2 \quad (5)$$

where

$$c \equiv 2(\lambda/r)^2 \quad (6)$$

Note that eq. (5) resembles the well-known Bradt-Peters formula⁵ with the "overlapping parameter"

$$b = c/(A_1^{1/3} + A_2^{1/3}) \quad (7)$$

decreasing with nuclear size as has been observed experimentally.⁶

Properties of r and λ

We have investigated various nuclear reactions in terms of eqs. (2) and (5) with two parameters r and λ . We find that both r and λ depend on the nature of the projectile. It follows that the nuclear size cannot be an intrinsic property but depends on the nature of the probe.

For p-A reactions, we get $r_p = 1.30 \pm 0.01$ fm. We note that the averages of mfp for π^+ and π^- reactions are practically the same; being 2.19 ± 0.35 and 2.09 ± 0.26 fm, respectively. This indicates that the difference between the density distributions of p and n inside a nucleus is rather small.

Conclusion

In summary, the heavy ion cross section derived from the optical model, eq. (5), is of the Bradt-Peters type and is similar to that of the hadron-nucleus (h-A), eq. (2). This property leads us to introduce an effective radius for h-A reactions:

$$R = (A^{1/3} - a/A^{1/3}) \quad (8)$$

the parameters r and $a = (\lambda/2r)^2$ being characteristic of the incident hadron. Since λ_p is less than λ_π and λ_K , the nucleus appears to be more transparent to meson than proton induced reactions, whereas all h-A cross sections follow the same R^2 dependence.

Footnotes and References

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Fig. 1. Reaction cross sections according to the optical model: (a) hadron-nucleus and (b) two like nuclei.
XBL 847-8527

Fig. 2. Heavy-ion cross sections for ^{56}Fe at 1.88 GeV/nucleon, LBL $\Delta Z \geq 1$; data errors less than 4% are not shown, ref. 6. The curve is the fit with eq. (5). Note its non-linearity in contrast to the Bradt-Peters formula, see text.
XBL 847-8530

Momentum Transfer in Intermediate Energy Collisions

L.G. Moretto and D. Bowman

The extensive measurements of momentum transfer in intermediate energy heavy ion collisions demand an elucidation of the essential kinematic and dynamic features of the associated interaction.

Let us consider the following greatly simplified model. Two nuclei of mass A and B collide in such a way that the nucleus B occludes a portion α of A and, correspondingly, A occludes a portion β of B. Let $\Delta\alpha$ and $\Delta\beta$ be the separation energies of the occluded parts α and β from their respective nuclei A and B.

The following questions arise:

A. If $\Delta\beta = \infty$

- 1) What is the minimum energy with which B must strike A so that the occluded portion α is shaved off and attaches itself to B?
- 2) At any higher energy than calculated in 1) what is the momentum of $A - \alpha$ and $B + \alpha$? Similarly, if $\Delta\alpha = \infty$ one can ask the questions symmetric to the ones above.

B. If neither $\Delta\alpha$ nor $\Delta\beta = \infty$

- 1) At what energy will any of the pieces α, β be shaved off?
- 2) At what energy will both of the pieces α, β be shaved off?

It is simple to show that the questions based in A have an answer that is purely kinematical and independent on the dynamics while the questions posed in B do require a solution of the dynamical problem. In other words the answers to A require solely the knowledge of A, B, α, β , $\Delta\alpha, \Delta\beta$, while the answers to B require additional information like restoring forces etc. Unfortunately this additional information is strongly model-dependent. However some illumination is already provided by answering the easier questions in A.

Let us consider first the case of A at rest being hit by B with momentum P. If the piece α sticks to B we have for the momentum of $A - \alpha$ and $B + \alpha$

$$\frac{P_{A-\alpha}}{P} = \frac{m_\alpha^*}{B + \alpha} \left(1 - \sqrt{1 - \frac{2\Delta\alpha}{m_\alpha^* v_0^2}} \right)$$

$$\frac{P_{B+\alpha}}{P} = 1 - \frac{m_\alpha^*}{B + \alpha} \left(1 - \sqrt{1 - \frac{2\Delta\alpha}{m_\alpha^* v_0^2}} \right)$$

$$\text{where } m_\alpha^* = \frac{(B + \alpha)(A - \alpha)}{A + B} ;$$

$$v_0 = \frac{B}{B + \alpha} v ;$$

$$v = \frac{P}{B} .$$

The complementary case involves again A being at rest, but, this time, picking up a piece β from the projectile B. We have

$$\frac{P_{A+\beta}}{P} = \frac{\beta}{B} \left[1 + \frac{A(B-\beta)}{(A+B)\beta} \left(1 - \sqrt{1 - \frac{2\Delta\beta}{m_\beta^* v_0^2}} \right) \right]$$

$$\frac{P_{A+\beta}}{P} = \frac{B-\beta}{B} \left[1 - \frac{A}{A+B} \left(1 - \sqrt{1 - \frac{2\Delta\beta}{m_\beta^* v_0^2}} \right) \right]$$

$$\text{where } m_\beta^* = \frac{(A + B)(B - \beta)}{A + B} ;$$

$$v_0 = \frac{A}{A + \beta} v ;$$

$$v = \frac{P}{B} .$$

It is interesting to notice that full momentum transfer (no shaving off of α or β) occurs when the square roots vanish, or when

$$\frac{2\Delta\alpha}{m_\alpha^* v_0^2} = 1 ; \quad \frac{2\Delta\beta}{m_\beta^* v_0^2} = 1 .$$

This occurs when the energy of B is

$$\frac{E}{B} = \Delta\alpha \frac{(B + \alpha)(A + B)}{(A - \alpha)B^2} ;$$

$$\frac{E}{B} = \Delta\beta \frac{(A + \beta)(A + B)}{(B - \beta)A^2} .$$

Notice also that at asymptotically large energies the momentum transfers tend to those one would have without binding, or $\Delta=0$.

In the spirit of the geometrical model one can attempt to calculate $\alpha, \beta, \Delta\alpha, \Delta\beta$ from the impact parameter. The quantities α, β are given by Świątecki as reported in ref. 1. For the quantities $\Delta\alpha, \Delta\beta$ we can take the energy of the new surface created by the abrasion process. For this we need to calculate the area of lateral surface defined by a cylinder and a sphere of radii r and R at an impact parameter b . If S is such a lateral area the total new surface created is $2S$. The area S can be obtained analytically

$$S = 8r \sqrt{R^2 - r^2 - b^2 + 2br} E\left(\frac{\pi}{2}, k\right)$$

$$= k = \sqrt{\frac{2br}{R^2 - r^2 - b^2 + 2br}}$$

for $R^2 - r^2 - b^2 > 2br \geq 0$, and

$$S = 4r \sqrt{\frac{1}{br}} \left\{ (R^2 - r^2 - b^2 - 2br) \times F\left(\frac{\pi}{2}, \frac{1}{k}\right) + 4br E\left(\frac{\pi}{2}, \frac{1}{k}\right) \right\}$$

for $R^2 - r^2 - b^2 < 2br$,

where E, F are the elliptic integrals of 1st and 2nd kind. As an example let us consider the reaction $\text{Be} + \text{Nb}$.

Fig. 1 demonstrates the impact parameters at which incomplete fusion processes become energetically possible for Be and Nb breakup. The area below each curve corresponds to the fragmentation region; above each curve is the complete fusion region. At impact parameters less than 3.5 fm the Be projectile is completely occluded by the Nb target; hence, Be fragmentation does not occur. Note that at all impact parameters less energy is required to shatter Be due to the smaller surface area created.

Fig. 2 shows the fraction of the initial momentum in the target-like (Nb) fragment as a function of bombarding energy per nucleon. The momentum transfer was calculated assuming projectile (Be) breakup at various impact parameters. Fig. 3 is the complement of Fig. 2 showing the fractional momentum in the projectile residue. As would be expected, central collisions lead to larger momentum transfer. In the limit of large bombarding energies the

Fig. 1. Incomplete fusion processes occur below each curve (see text). XBL 8511-12217

Fig. 2. Momentum of Nb-like fragment. XBL 8511-12219

Fig. 3. Momentum of Be-like fragment. XBL 8511-12220

momentum transfer at any given impact parameter tends to a constant as $\frac{\Delta\alpha}{E_{lab}} \rightarrow 0$.

In Fig. 4 the fractional momentum of the target-like fragment (Fig. 2) has been integrated over impact-parameter (weighted by impact parameter). Again as the bombarding energy is increased the momentum transfer tends to a constant.

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Fig. 4. Momentum of Nb-like fragment.

XBL 8511-12218

The Role of Surface in Nuclear Shattering

Luciano G. Moretto

Aichelin and Hüfner¹ have postulated that fragment formation in the intermediate energy region can be viewed as a shattering process. They attempted to calculate the fragment mass distribution in terms of a least biased approach that was later shown² to be a saddle point approximation to the Euler number partition.

Among the many shortcomings of this approach is its lack of energy dependence and its inability to connect the mass distribution to other observables. A possible way to introduce an energy dependence in the problem is suggested by the fact that it takes energy to produce the extra surface associated with fragment formation. In what follows a way is shown to evaluate the mass distribution with the constraint of a fixed amount of generated surface. As in ref. 1 we define a probability $P(m,a)$ of producing a fragment of mass a with multiplicity m . The constraints are for each a

$$\sum_m P(m,a) = 1 \quad ; \quad (1)$$

$$\sum_m \sum_a maP(m,a) = N \quad , \quad (2)$$

N being the mass of the object being fragmented;

$$\sum_m \sum_a Kma^{2/3}P(m,a) = S \quad , \quad (3)$$

S being the surface produced. The information associated with P modified by the constraints is

$$I = \sum_m \sum_a [P(m,a) \ln P(m,a) - K(a)P(m,a) + DmaP(m,a) + Ama^{2/3}P(m,a)] \quad (4)$$

where $K(a)$, D , A arise from the introduction of the constraints.

Minimization of the information I gives

$$P(m,a) = e^{K(a)-1} e^{-m(Da + Aa^{2/3})} = C(a) e^{-m(Da + Aa^{2/3})} \quad (5)$$

Applying eqs. (1), (2), and (3) to (5) one obtains:

$$C(a) = 1 - \exp - (Da + Aa^{2/3}) \quad (6)$$

$$\sum_a \frac{a}{\exp(Da + Aa^{2/3}) - 1} = N \quad (7)$$

$$\sum_a \frac{a^{2/3}}{\exp(Da + Aa^{2/3}) - 1} = S \quad (8)$$

Summing $P(m,a)$ over m one has

$$P(a) = \frac{1}{\exp(Da + Aa^{2/3}) - 1} \quad (9)$$

By solving eqs. (7) and (8) simultaneously for D and A and substituting the values so obtained in eq. (9) one arrives at the derived distribution. If no restriction is imposed upon the surface, then $A = 0$ which defines the unconstrained surface S_0 . If a restriction is imposed by fixing S near S_0 one can linearize the problem and obtain an analytical result.

$$\Delta A = \frac{\Gamma(\frac{5}{3})\Gamma(\frac{5}{3}) D_0^{2/3} \frac{\Delta S}{S_0}}{\left[-\frac{4}{3}\Gamma(\frac{4}{3})\Gamma(\frac{4}{3}) + \left\{ \frac{5}{3}\Gamma(\frac{5}{3})\Gamma(\frac{5}{3}) \right\}^2 / \left\{ 2\Gamma(2)\Gamma(2) \right\} \right]}$$

$$\Delta D = -\Delta A \frac{\frac{5}{3}\Gamma(\frac{5}{3})\Gamma(\frac{5}{3})}{2\Gamma(2)\Gamma(2)}$$

$$D_0 = \frac{\sqrt{\Gamma(2)}}{\sqrt{N}}$$

Numerically one has

$$\Delta A = -1.618305 D_0^{2/3} \frac{\Delta S}{S_0}$$

$$\Delta D = -0.971156 \Delta A$$

$$D_0 = \frac{1.2825}{\sqrt{N}}$$

As an example, Fig. 1 shows the resulting mass distribution assuming $N = 200$. The three curves correspond to

$$\frac{\Delta S}{S_0} = 0; 0.2; -0.2$$

One can readily see that by requiring more surface area one favors the formation of light fragments and by requiring less surface area one enhances the production of heavy fragments.

Lastly, it remains to be established how much energy is invested in surface production in any given reaction. This may not be easy to determine. How-

ever it may be possible to infer that from the determination of the total fragment kinetic energy in the center of mass of the fragmenting nucleus. If the virial theorem can be applied, then a relation must exist between the average total kinetic energy and the average potential energy which is approximately proportional to the average produced surface. One could try $\bar{E}_{kin} \approx a_s \bar{S}$ where a_s is the liquid drop surface energy coefficient.

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Fig. 1. Mass distribution from the fragmentation of a system with mass 200. The curve labeled $\frac{\Delta S}{S_0} = 0$ corresponds to the use of unconstrained surface; the curves labeled $\frac{\Delta S}{S_0} = \pm 0.2$ correspond to an increase (decrease) of 20% of the surface as compared to its unconstrained value.

XBL 862-424

Probing the Tilting Mode in Nuclear Reactions*

Thomas Døssing[†] and Jørgen Randrup[‡]

An expression is derived for the cross section near the beam in direct nuclear reactions. It contains information on the degree of excitation of the tilting mode, and it reduces to the standard result when applied to fission. An instructive application is made to the damped reaction 710 MeV $^{86}\text{Kr} + ^{139}\text{La}$. In quasi fission reactions the relaxation of the tilting mode is expected to be incomplete.

Angular momentum related observables have been studied for some time in damped nuclear reactions, and recently also in the more intimate and longer lasting quasi fission reactions. The angular momenta of the reaction products yield important information about the reaction dynamics. A dynamical theory for the accumulation of angular momentum in damped nuclear reactions was recently developed¹ and confronted with data.² In that work it was shown that the tilting mode (which is associated with the projection of the total angular momentum $\mathbf{J}$ on the dinuclear axis $\mathbf{R}$) is particularly intricate: it has generally a rather long relaxation time which varies with impact parameter in a manner opposite to the other dinuclear rotational modes so that the most central reactions have the longest relaxation times.

The tilting mode is well known from nuclear fission where it can be related to the shape of transition configuration for which the statistical excitation of the mode is frozen in. Knowledge of the total angular momentum and the nuclear temperature permits the extraction of experimental information on the transition shape from fission fragment angular distributions.

We have made an analogous treatment for direct nuclear reactions, such as damped and quasi fission reactions. The cross section close to the beam is shown to be simply related to the degree of excitation of the tilting mode, as in nuclear fission. Furthermore, the result is illustrated by calculations for damped reactions, and recent quasi fission data are briefly discussed.

The temporal evolution of a direct reaction is illustrated in Fig. 1, which emphasizes various angles and directions relevant to the present discussion. The beam enters from the left and leaves to the right, and the total angular momentum $\mathbf{J}$, which is equal to the initial orbital angular momentum $\mathbf{L}_i$, points upwards. In the course of the reaction, angular momentum is exchanged between the relative and intrinsic rotational modes, so that the orbital angular momentum $\mathbf{L}$ evolves gradually from its initial value $\mathbf{L}_i$ to its final value $\mathbf{L}_f$. The trajectory of the direction $\hat{\mathbf{L}}(t)$ is shown in the polar region of the unit sphere in the figure. On the same unit sphere is shown the evolution of the direction $\hat{\mathbf{R}}(t)$ of the relative position $\mathbf{R} = \mathbf{R}^A - \mathbf{R}^B$ (where A,B refers to the projectile-like, target-like reaction partner). Prior to the reaction the two nuclei approach on a Coulomb trajectory lying in the entry plane. During the reaction phase, the directional change of the orbital angular momentum forces the relative trajectory to wander away from the entry plane (although usually not very far). The beginning and end of the reaction phase are indicated by the vertical bars on the trajectory. After the reaction the two products recede on another Coulomb trajectory lying on the (generally different) exit plane which is tilted by the angle ψ relative to the entry plane (hence the name tilting mode). The observed scattering angle θ is the distance (on the unit sphere) from the final direction $\hat{\mathbf{R}}(\infty)$ to the beam direction, as indicated in the figure.

Fig. 1. Schematic illustration of various angles and directions relevant to the discussion of a damped nuclear reaction.

XBL 8510-4406

Our result may be written in the following simple form:

$$d\sigma/d\theta \approx (d\sigma/d\theta)_0 C_0 (J_0/2K_0) \sin \theta \quad (1)$$

where $(d\sigma/d\theta)_0 = f(\theta) + f(-\theta)$ is the external differential cross section as calculated with the tilting ignored (i.e., assuming $K_0=0$). (It should be noted that if orbiting conditions prevail there are additional contributions to the forward cross section from $\theta_f \approx 2\pi, 4\pi, \dots$; if these contributions are significant they must be added in $d\sigma/d\theta$ in a similar manner.) Finally, we note that backscattering of course can be treated analogously by expanding $d\sigma/d\theta_f$ around $\theta_f = \pi$ (and, if required, also around $3\pi, 5\pi, \dots$).

The tilting correction factor C_0 is displayed in Fig. 2 as a function of the scattering angle, for different values of K_0/J_0 . The tilting of the reaction plane disperses cross section away from zero degrees and into scattering angles of the order of K_0/J_0 . In consequence, the correction factor rises from zero at $\theta=0$ to its maximum value ≈ 1.175 over an angular range of $\approx K_0/J_0$ and then decreases slowly towards unity for larger angles. A convenient measure of the range of angles affected by the tilting-induced depression is provided by that angle $\theta_{1/2}$ for which the correction factor has reached half its maximum value. This angle is to a good approximation given by $\sin \theta_{1/2} \approx K_0/2J_0$ so that K_0/J_0 can be experimentally determined by measuring $\theta_{1/2}$, in analogy with fission.

It should be noted that when $f(\theta)$ is constant, as in fission, the angular variation of the cross section arises entirely from the correction factor (which must be properly normalized when $K_0/J_0 \geq 1/2$). Thus our result [eq. (1)] can be regarded as a generalization of the theory for fission angular distributions to direct reactions, however with the important difference that for direct reactions the quantity K_0 represents the dynamically accumulated excitation of the tilting mode, rather than the value characterizing the statistical equilibrium distribution.

After the reaction phase the excited product nuclei evaporate light particles, mostly neutrons in the cases of present interest. The associated nuclear

Fig. 2. The tilting correction factor $C_0(J_0/2K_0)\sin\theta$ shown as a function of the scattering angle θ for three values of K_0/J_0 . XBL 8510-4407

recoil momenta will produce additional fluctuations in the tilting angle. The correction for neutron evaporation is usually quite small, of the order of five percent.

Finally, we wish to comment briefly on recent experimental results for the so called quasi fission events.³ This class of event is thought to be associated with fairly central reactions and characterized by reaction times which are substantially (i.e., 3–4 times) larger than those for ordinary damped reactions. If indeed so, the relaxation time for the tilting mode, which is inversely proportional to the square of the rotational frequency, will increase even more than the reaction time. As a consequence, the tilting mode may be expected to receive rather little excitation in a quasi fission reaction, and less so the smaller the reaction time. This feature might explain recent experimental results indicating incomplete tilting relaxation³ and our present work may be of use in the further analysis of the phenomenon.

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- ‡ Supported in part by NORDITA, Copenhagen, Denmark.
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Quantal Foundation of the Nucleon Exchange Transport Theory*

J. Randrup†

Damped nuclear reactions have been studied extensively through the last decade. Particular interest has focussed on the role of multiple nucleon transfer as a dissipative mechanism in the dinuclear system. In this connection, a theory of transfer-induced transport in nuclear reactions was developed.¹ This theory gives a unified treatment of several different observables of interest, including the partition of charge and mass on the two fragments, their accumulated angular momenta and intrinsic excitation, and the energy and direction of the relative motion. Through consistent calculations of the various effects of the nucleon transfers, general expressions were derived for the transport coefficients describing the dissipative evolution of the considered macroscopic observables. Moreover, from certain idealizations, very simple formulae were obtained for the transport coefficients so that the calculation of the entire dynamical evolution of a damped reaction becomes a fairly easy task.

The purpose of the present work is to undertake a more formal discussion of the key elements in the nucleon-exchange transport theory in order to elucidate the principal characteristics, validity and limitations of the theory. Particular emphasis is put on bringing out the quantal foundation of the theory. This important aspect has so far not received a thorough discussion in the literature, and is not readily discernible from the simple, quasi classical appearance of the resulting formulae.

A central problem, which has given rise to much debate over the past several years, is the proper form of the normal component of the friction coefficient. In a quantal description, the motion of the nucleus in the normal direction is described by

standing waves, while traveling waves may be used in the directions parallel to the surface. A standing wave can be considered as a superposition of two degenerate waves traveling in opposite directions. This degeneracy is broken when the system is viewed from a moving frame and each nucleonic eigenstate acquires a Doppler splitting so that a level with energy $\epsilon = p^2/2m$ appears to have the momentum components $p_{\pm} = p \pm mU$ where U is the motion of the observer. The quantum mechanical transition amplitudes are largest when the associated time dependent phase is stationary. This condition implies that transfers occur predominantly between levels whose eigenvalues differ by the Doppler shift $\pm U$. This result in turn leads to the standard formula for the energy dissipation rate and hence for the radial friction coefficient. Thus the formulas originally derived¹ on a semi classical basis have a solid quantum mechanical foundation.

The study also provides new insight into the behavior of the friction coefficients at large separations where the transferring nucleons must negotiate a potential barrier between the two nuclear wells. In particular, it is found that the form factor for initial friction will dominate over the tangential one for distant configurations (see subsequent contribution), a fact with important bearing on the interpretation of existing data.

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Transfer-Induced Transport in Slightly Damped Nuclear Reactions*

J. Randrup†

Recent advances in our understanding of the nuclear one-body dissipation mechanism (see preceding contribution) have shown that at large separations the radial friction form factor will greatly exceed the tangential one. This effect is easily understood qualitatively. Due to the presence of a potential barrier between the two nuclear potential wells, the transferred nucleons are unlikely to have much tangential motion. Therefore the radial friction coefficient is enhanced. This feature has not yet been included in dynamical transport calculations but it is expected that it will significantly affect the results for slightly damped collisions. Below we mention two examples.

When the two friction form factors are of comparable size (as they are approximately for more intimate reactions where $c_r \approx 2c_t$) the dissipation of relative energy in a peripheral reaction is caused mainly by the tangential friction, since the relative motion is predominantly tangential during the reaction. One would then expect a very simple general relationship between the dissipated energy Q and the loss in an orbital angular momentum, ΔL , namely $Q \approx \omega_0 \Delta L$ where $\omega_0 = L/\mu R_0^2$ is the angular frequency of the relative motion at the closest approach. However, when $c_n \gg c_t$ the above relation is no longer valid, since a substantial fraction of Q is produced by radial friction. This new insight makes it desirable to reconsider the situation with the refined friction form factors taken into account and, indeed, simple estimates provide hope that existing γ -multiplicity data might then be reasonably understood within the theory.

For large separations most, or all, transfers occur by tunneling through the barrier between the two nuclides. The penetrability $P(\epsilon_n)$ is then a strongly increasing function and the nucleons near the Fermi

surface, which are those that are Pauli allowed to transfer, pay a high penalty for having transverse motion. Therefore, the dominant transfers are those which have the highest possible normal energy ϵ_n . It then follows that in a fairly tangential reaction, where the radial velocity is relatively small throughout the interaction, the dissipated energy per transfer is $\frac{m}{2} U^2$, on the average. This expectation is indeed borne out by experimental studies of quasi-elastic transfer reactions.

It is interesting to note that in a model where the transferring particles have no intrinsic motion one would generally obtain an exciton energy of $\frac{m}{2} U^2$. A peripheral reaction is therefore not well suited for discriminating between such a model and our present model which incorporates the Fermi motion of the nucleons. Due to the coupling between the intrinsic motion and the relative motion, the exciton energy is generally of order $\frac{1}{2} U P_F \gg \frac{m}{2} U^2$ in the nucleon-exchange transport model. However, in a peripheral reaction the transferring nucleons have a momentum which is nearly perpendicular to the relative velocity and then the coupling becomes ineffective.

Therefore, a better test of this central ingredient in the model might be made in gentle head-on reactions where the relative motion is optimally aligned with the momenta of the transferring nucleons, and it would be interesting to pursue this possibility experimentally.

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* Condensed from preprint NORDITA-85/29; to appear in Nuclear Physics A.

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On the Extra Energy Needed to Form a Compound Nucleus*

J. Błocki, H. Feldmeier, and W.J. Świątecki

A macroscopic model incorporating one-body dissipation in the equations of motion was used to study the head-on collisions of two nuclei characterized by a range of sizes and asymmetries. The extra energy above the Coulomb barrier needed to achieve fusion was shown to appear at a fissility parameter

$x=0.723$ and to rise with an initial "steepness parameter" $a=18$.

Footnotes and References

* Condensed from GSI Scientific Report 1984, GSI 85-1, March 1985, p. 131.

Dynamical Hindrance to Fusion in Nucleus-Nucleus Collisions

J. Błocki, H. Feldmeier, and W.J. Świątecki

The work described in the previous contribution has been extended to include heavier and more asymmetric systems, covering essentially the full range of target-projectile combinations relevant to fusion experiments. A contour plot of the extra energy above the Coulomb barrier needed for fusion has been constructed as a function of the mass numbers of the colliding nuclei. A parameterization of this two-dimensional surface is possible in terms of a single mean fissility parameter, which is obtained by

averaging over the effective fissility of the tangent configuration and the fissility of the compound system, the latter being accorded twice the relative weight. The dynamical calculations illustrate graphically the distinction between fusion and fast fission and predict a time scale for the latter process in the general range 10^{-21} – 10^{-20} sec (but sometimes longer), depending on the masses and energies of the colliding nuclei. The work is being prepared for publication.

Refinements in the Theory of Heavy Particle Radioactivity

Y.-J. Shi and W.J. Świątecki

In the recent treatment of heavy-particle radioactivity as an asymmetric case of spontaneous fission,¹ the parent as well as the daughter nuclei were assumed spherical, with radii taken to be given by a nominal standard formula. We have investigated three refinements to this model: (i) deviations of the radii from the standard formula, (ii) the presence of

ground-state deformations of the fragments (as well as deformations at scission) and (iii) the influence of the deformations on the shell effects in the system.

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The Order-to-Chaos Transition and the Nature of Nuclear Dynamics

Y.-J. Shi and W.J. Świątecki

Evidence is accumulating for the validity of the expectation that, when the nucleonic motions in a nucleus are ordered, the nucleus as a whole should behave as an elastic solid, whereas when the nucleonic motions are chaotic, it should behave like a very viscous fluid, with a novel type of viscosity. In the intermediate regime a visco-elastic behavior is anticipated. In order to illuminate these complex phenomena we have undertaken an extensive numerical study of the transfer of energy from a time-

dependent container (the idealized nuclear potential) to an ideal gas of independent point particles filling the container. Depending on the symmetries of the container and the nature of the time dependence, this transfer is observed to be elastic, visco-elastic or dissipative. These studies are helping to test the range of validity of simple formulae appropriate in the extreme limiting cases of fully ordered or fully chaotic particle motions and to understand the complex intermediate regime.

The Effect of the Diffuseness of the Nuclear Surface on the Intensity of Fermi Jets

W.J. Świątecki

The discussion of the pre-equilibrium emission of nucleons during a nucleus-nucleus collision was treated in ref. 1 according to the Fermi-Jet model. In the above reference the model was idealized to the case of sharp-surfaced potential wells. It is possible to generalize some of the analytical results to the case of diffuse wells. The principal effect of the dif-

fuseness is to increase the intensity of the jets by some tens of percent, depending on the sizes of the nuclei.

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A Mnemonic for Feigenbaum's Universal Number δ^*

W.J. Świątecki

Feigenbaum's universal number δ ($\approx 4.6692 \dots$), which governs the transition from order to chaos in many dynamical systems, is closely approximated by $\delta \approx \sqrt{137/2\pi}$. This is equivalent to the following mnemonic: "the smallest resolvable area in phase space allowed by quantum mechanics ($\hbar/2$), when

expressed in the natural electromagnetic unit of action (e^2/c), is equal to the area of a circle whose radius, to within 2 parts in 10^4 , is Feigenbaum's universal number δ ."

Footnotes and References

- * Condensed from LBL-19591, May 1985.

Friction in Nuclear Dynamics*

W.J. Świątecki

The problem of dissipation in nuclear dynamics is related to the breaking down of nuclear symmetries and the transition from ordered to chaotic nucleonic motions. In the two extreme idealizations of the perfectly Ordered Regime and the fully Chaotic Regime, the nucleus should behave as an elastic solid or an overdamped fluid, respectively. In the intermediate regime a complicated visco-elastic behavior is expected. The discussion is illustrated by a simple estimate of the frequency of the giant quad-

rupole resonance in the Ordered Regime and by applications of the wall and window dissipation formulae in the Chaotic Regime.

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On the Inertial Parameter at High Angular Momentum and Excitation Energy*

J.L. Egido[†] and J.O. Rasmussen

New high-resolution and high-efficiency devices allow very precise measurements at high angular momentum and high excitation energy. Recently Deleplanque, *et al.*¹ have done some experiments with ¹²⁶Sn on ⁴⁰Ar and they have obtained very accurate information about the moments of inertia $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ at high excitation energy. These quantities are defined by

$$\mathcal{J}^{(1)} = \frac{J}{\omega} = \frac{1}{2} \left(\frac{dE}{dJ^2} \right)^{-1} \quad (1)$$

and

$$\mathcal{J}^{(2)} = \frac{dJ}{d\omega} = \left(\frac{\partial^2 E}{\partial J^2} \right)^{-1} \quad (2)$$

with $J = \sqrt{I(I+1)}$.

From its own definition we see that $\mathcal{J}^{(2)}$ is a very sensitive quantity: it corresponds to the slope of the curve I as a function of ω .

Theoretically,² depending on which approximation is used one has for the inertial parameters several definitions. The most widely used are in connection with the self-consistent cranking model, which has been used with considerable success to describe the spectra of well deformed nuclei in the

vicinity of the yrast line.

The self-consistent moment of inertia is defined as

$$\mathcal{J}_{sc} = \frac{\langle J_x \rangle}{\omega} = \frac{\langle \Delta J_x^2 \rangle \langle J_x \rangle}{\langle H \Delta J_x \rangle}, \quad (3)$$

and it corresponds to the mean field approximation to $\mathcal{J}^{(1)}$. To obtain a theoretical approach to $\mathcal{J}^{(2)}$ one has to get further correlation, and this is usually done in the RPA approach or with linear response theory. It is called Thouless-Valatin moment of inertia, and it is given by

$$\mathcal{J}_{TV} = (J_x^* J_x) \begin{vmatrix} A & B \\ B^* & A^* \end{vmatrix}^{-1} \begin{vmatrix} J_x \\ J_x^* \end{vmatrix} \quad (4)$$

where A and B are the RPA matrices. The Inglis moment of inertia $\mathcal{J}_{Ing}$ corresponds to the limit of $\mathcal{J}_{TV}$ when the correlations between the quasiparticles are neglected. Calculations of these quantities have been done in ref. 2 for the yrast line of the nuclei ¹⁶⁴Er and ¹⁶⁸Yb in the frame of the self-consistent cranking model with the Baranger-Kumar hamiltonian and configuration space. In ref. 3, these calculations were extended for $\mathcal{J}_{sc}(\mathcal{J}^{(1)})$ up to the quasicontinuum by solving the Temperature-Dependent Hartree-Fock Bogoliubov equations in the rotating

frame.

The purpose of this work is to calculate $\mathcal{J}^{(2)}(\mathcal{J}_{IV}$ and $\mathcal{J}_{Ing})$ from the yrast line up to the continuum using the Temperature-Dependent Random-Phase Approximation in the Rotating system.

A detailed description of our theory and model will be published.⁴ Here in this report we shall concentrate on $\mathcal{J}_{IV}$ and simply sketch the main steps in the calculation of this quantity: We first solved³ the Finite-Temperature-Hartree-Fock-Bogoliubov (FTHFB) equation for different values of T and ω , so that the whole range $0 \leq \omega \leq .6$ MeV, and $0 \leq T \leq 1.0$ MeV was covered; relation (3) provided us $\mathcal{J}_{sc}$. Second in each point of the grid the generalization of eq. (4) for finite temperatures was solved to finally get $\mathcal{J}_{IV}$.

In Fig. 1a we show the self-consistent moment of inertia as a function of the angular velocity for constant temperatures for the nucleus ^{164}Er . It is important to notice that we have solved the FTHFB equations with constant ω , in steps of $\Delta\omega=.025$, instead of constant I (i.e. for simplicity we did not use the gradient method). Because of this we do not see the backward parts of the backbendings, if any, but only alignments. For $T=0.0$ we see in Fig. 1a a strong neutron alignment at $\omega \sim .225$, a smaller proton alignment at $\omega \sim .325$, and a much smaller neutron alignment at $\omega \sim .525$. At $T=.2$ and $.4$ MeV we still observe some structure, although smoothed out, and an increase of the moment of inertia caused by the reduction of the pairing correlations with growing temperatures. For $T > .5$ MeV the pairing gap collapses and as a result $\mathcal{J}_{sc}$ remains more-or-less constant.

In Fig. 1b we draw $\mathcal{J}_{IV}$ for different temperatures as a function of the angular velocity. From its definition we know that $\mathcal{J}_{IV}$ goes to $\pm\infty$ at each up-backbending. Since we are solving the equations for finite step size $\Delta\omega$, the height of the peak in each up-bending does not necessarily mean larger alignment but only how near our actual ω is to ω_{crit} . At $T=0$, as expected, we get three peaks. At $T=.2$ and $.4$ MeV only the peaks corresponding to large alignments remain; the smaller one at $\omega \sim .525$ is already washed out at these low temperatures. At higher tempera-

tures little structure remains and the moment of inertia converges to the rigid-body value. The comparison with the experimental values¹ is not straightforward: for low angular velocities their values correspond mostly to the yrast line, and the agreement with ours is rather good; for higher angular velocities their window in energy is much larger, so that it is difficult to compare. Nevertheless the general trends to smooth out do agree in both experiment and theory.

In conclusion for the first time we have done a fully self-consistent calculation of the moment of inertia $\mathcal{J}^{(2)}(\mathcal{J}_{IV})$ at high angular momentum at high excitation energy. We find qualitative agreement with the experiment.

Fig. 1. (a) The self-consistent moment of inertia $\mathcal{J}^{(1)}$ versus the cranking velocity for different temperatures. (b) The Thouless-Valatin moment of inertia $\mathcal{J}^{(2)}$ versus the cranking velocity for different temperatures.

XBL 8511-4547

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The Effect of Temperature Fluctuations on Deformation Parameters

J.L. Egido,* C. Dorso,† J.O. Rasmussen, and P. Ring‡

In recent years much experimental as well as theoretical effort has been devoted to understanding properties of nuclei under extreme conditions, such as high angular momentum and/or high excitation energy.¹ On the experimental side several new phenomena have been discovered. Some examples are the observed irregularities in the yrast band of a cold nucleus and the existence of Giant Resonances built on excited states.² The Self-consistent Cranking Model³ has been successfully used for the description of the yrast line of a cold heavy nucleus. For moderately higher excitation energy one still has to consider the pairing degree of freedom as well as the temperature dependence, which complicates the use of realistic forces in calculations of Hartree-Fock-Bogoliubov type. Consequently only the semiclassical method of Strutinsky generalized to finite temperature and superfluid nuclei has been used⁴ as an approximation. Recently the Finite Temperature Hartree-Fock-Bogoliubov has been proposed⁵ and solved⁶ for separable forces with the Baranger-Kumar Hamiltonian and configuration space.

In all the above calculations no attention has been paid to the fluctuations due to the finite temperature. However, simple models,^{7,8} as well as more realistic calculations,⁹ have shown that the effect of such fluctuations can be very important for quantities such as the pairing gap even at low temperatures ($T \gtrsim 5$ MeV). The motivation of this work was to extend such investigations to other degrees of freedom such as the deformation parameters a_0 and

a_2

$$a_0 = \beta \cos \gamma$$

$$a_2 = \beta \sin \gamma \quad ,$$

which for a deformed nucleus are related to the quadrupole moments. Details of the work will appear in a later paper;¹⁰ here we only mention the main steps.

If one considers a_0 and a_2 as collective coordinates, it is possible to derive a classical hamiltonian function in the Adiabatic Time-Dependent Hartree-Fock Theory

$$H(a_0, a_2, \dot{a}_0, \dot{a}_2) = \frac{1}{2} B_{00} \dot{a}_0^2 + \frac{1}{2} B_{22} \dot{a}_2^2 + B_{02} \dot{a}_0 \dot{a}_2 + V(a_0, a_2) \quad .$$

$V(a_0, a_2)$ is given by the temperature-dependent mean-field energy, and the mass parameters B_{ij} are given by

$$B_{\mu\nu} = \frac{1}{2} \sum_{kl} \frac{q_{lk}^\mu q_{lk}^\nu}{(E_l - E_k)^3} (f_k - f_l) \quad ,$$

where q^μ is the supermatrix,

$$\begin{vmatrix} Q^{11} & Q^{20} \\ -Q^{02} & -Q^{11T} \end{vmatrix}$$

corresponding to the multipolar operators $r^2 Y_{20}$ or $r^2 Y_{22}$. E_k are the quasiparticle energies,

$$\begin{vmatrix} \tilde{E}_k & 0 \\ 0 & -E_k \end{vmatrix}$$

and f_k the occupation factors of the Fermi-Dirac distribution at temperature T , in matrix form,

$$\begin{vmatrix} f_k & 0 \\ 0 & 1-f_k \end{vmatrix}$$

The probability for the nucleus having the deformation a_0, a_2 is given by

$$P(a_0, a_2) \sim$$

$$|B_{00}(a_0, a_2) B_{22}(a_0, a_2) - B_{20}^2(a_0, a_2)|^{1/2} \cdot \exp(-F(a_0, a_2)/T)$$

$F(a_0, a_2)$ is the free energy obtained from $V(a_0, a_2)$, varying a_0, a_2 independently. In principle, one should also consider the pairing degree of freedom as an independent variable, but then the calculations become very time consuming, so we approximate these calculations by solving the gap equations for each point of the plane a_0, a_2 to find the self-consistent gap for this deformation. The chemical potentials λ_Z, λ_N were adjusted to get the right particle numbers. In our calculations we use the Baranger-Kumar¹¹ hamiltonian and configuration space. If one assumes that the mass parameters do not depend on the deformations a_0 and a_2 , the square root factor can be suppressed from the expression for $P(a_0, a_2)$.

In Fig. 1a-f we show the probability distribution $P(\beta, \gamma)$, without mass dependence, for the nucleus ^{158}Er at $I=0$ for the temperatures $T=.2, .8, 1.0, 1.2, 1.4$ and 2.0 MeV. $P(\beta, \gamma)$ is normalized in such a way that the maximum value for a given temperature is unity. Each line in the contour plots differs in $\pm .1$ from the nearby lines. For $T=.2$ MeV we have a strongly peaked distribution around the axially symmetric minimum at $\beta=.23$. At $T=.8$ the distribution softens in all directions. At $T=1.0$ the minimum is still on the prolate side but on the oblate side at $\beta \sim .1$ there is up to half of the probability density of the prolate maximum. At $T=1.2$ the shifting towards the oblate side continues, while at $T=1.4$ the maximum of the distribution is already at $\beta=0$. At $T=2.0$ MeV the distribution is essentially that of a spherical vibrator. The full probability distribution¹⁰ $P(a_0, a_2)$, i.e. without neglecting the mass dependence, looks very similar to the distribution shown in Fig. 1, the only difference being that the whole distribution is somewhat shifted to the oblate shapes.

In the upper part of Fig. 2 we show a_0 , the self-consistent value of a_0 , which corresponds to the value of a_0 in the energy minimum in the plane a_0, a_2

Fig. 1. The probability distribution $P(a_0, a_2)$ for different temperatures for the nucleus ^{158}Er . The mass dependence has been neglected. XBL 8511-4549

Fig. 2. In the upper part are shown the parameters a_0 and a_2 in different approximations (see text) versus the temperature. In the lower part are shown deviations $\sigma_{a_0}^2, \sigma_{a_2}^2$. In both cases the left scale applies for a_0 , whereas the right hand one is for a_2 .

XBL 8511-4548

for a given T . Since we are at $J=0$, the shape parameter γ is 0° and therefore $a_{2\kappa}=0$. ($a_{0\kappa}=\beta$) for all temperatures. Also represented are the corresponding values of a_0 and a_2 but taking into account the temperature fluctuations, i.e.

$$\overline{a_{0,2}} = \langle \overline{a_{0,2}} \rangle = \int a_{0,2} P(a_0, a_2) da_0 da_2$$

$a_{0\kappa}$ and $\overline{a_0}$ are referred to the scale on the left, whereas $\overline{a_2}$ is referred to the scale on the right. Shape parameters $\overline{a_{0\kappa}}$ and $\overline{a_{2\kappa}}$ are average values calculated taking into account the mass dependence of the probability, $\overline{a_0}$ and $\overline{a_2}$ are the corresponding quantities but neglecting the mass dependence in $P(a_0, a_2)$. At temperatures $0 \leq T \leq .5$ parameter $a_{0\kappa}$ (or β) slightly rises, mainly because of the reduction of pairing correlations with growing temperature. Between $T=.6$ and 1.1 MeV the temperature destroys the shell effects and we observe a diminution of the deformation. For $T > 1.1$ MeV the fluctuations are so large that the mean field approach is no longer a good one and the deformation drops dramatically from .16 at $T \sim 1.1$ MeV to zero at $T \sim 1.4$ MeV.

The average values $\overline{a_0}$ behave in a similar manner to $a_{0\kappa}$ for temperatures $T \leq 1.1$ MeV, but for T larger than 1.1 MeV, $\overline{a_0}$ does not decrease but approaches the value $\sim .13$, which can be understood from the consideration of the values of $P(\beta, \gamma)$ in Fig. 1. The parameter $a_{2\kappa}$, as mentioned above, is always zero because of axial symmetry; $\overline{a_2}$ rises with a rather steep slope from 0 to .060 at $T \sim 1.1$, then remains almost constant around the value .065. This behavior can also be understood from Fig. 1. Parameter $\overline{a_{2\kappa}}$ is similar to $\overline{a_2}$ for all temperatures. Parameter $\overline{a_{0\kappa}}$ looks like $\overline{a_0}$ for temperatures lower than 0.5 MeV but for higher temperatures exhibits smaller values. In both cases the sharp collapse of the deformation is smeared out by the temperature fluctuations. The neglect of the mass dependence overemphasizes this effect.

In the lowest part of Fig. 2 the fluctuations

$$\sigma_{a_{0,2}}^2 = \langle \overline{a_{0,2}}^2 \rangle - \langle \overline{a_{0,2}} \rangle^2$$

are represented. Again the left hand scale is for a_0 and the right hand scale for a_2 . Both of them behave in a similar way. They rise quickly from $T=0$ to $T \sim 1.1$ MeV and then stabilize for higher temperature.

In conclusion, we have for the first time self-consistently taken into account the temperature fluctuation in the calculation of the deformation parameter for ^{158}Er in realistic calculations. The effects on a_0 are large for $T \geq 1.1$ MeV; on a_2 they become appreciable already for small temperatures.

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Transfer Involving Deformed Nuclei^{*,†}

J.O. Rasmussen, M.W. Guidry,[‡] and L.F. Canto[§]

We review results of 1- and 2-neutron transfer reactions at near-barrier energies for deformed nuclei. Rotational angular momentum and excitation patterns are examined. A strong tendency to populating high spin states within a few MeV of the yrast line is noted, and it is interpreted as preferential transfer to rotation-aligned states.

In a deformed field the wavefunction for a particle at the nuclear surface will be concentrated in particular regions. Fig. 1 illustrates, for a typical orbit important for work we will discuss, the ^{161}Dy ground state neutron $5/2^+ [642]$.

In the simple model for transfer employed in ref. 1 the probability of particle transfer as a function of orientation angle of the rotor depends on selecting an optimum orientation such that the nuclei overlap neither too weakly (suppressed barrier penetration) nor too strongly (suppression by absorption into more complicated channels), and asking whether the relevant Nilsson orbit has lobes lying on the ion-ion axis for those orientations. If the Nilsson orbital of the transferred neutron has a dominant lobe on the surface, this fixes the process to a single root of the quantum number function and hence a fairly sharply defined value of Coulomb-excited rotational angular momentum. If there is more than one surface lobe of comparable strength, novel interference effects could arise.

Several studies of neutron transfer with deformed nuclei have recently been reported. They generally employ high resolution gamma-ray or conversion-electron detection to identify products uniquely and to furnish information on the rotational angular momentum involved. Particle detectors do not have the mass resolution nor energy resolution to resolve clearly the final nuclei and the states populated for rare-earth and actinide deformed regions.

Himmele *et al.*² at GSI, Darmstadt, have used the system of ^{184}W on ^{238}U . They obtained results

Fig. 1. Contour plot of the wave function of a neutron in the Nilsson orbital $5/2^+ [642]$. XBL 853-1565

for 1- and 2-neutron transfer probabilities in both directions. Their tunneling slope parameters are not in the 2:1 ratio expected for 2- and 1-neutron transfer.

Macchiavelli *et al.*³ at LBL have used germanium gamma ray detection to study ^{132}Xe on ^{154}Sm , ^{176}Yb , and ^{171}Yb . They obtained results for 1- and 2-neutron transfer probabilities out of the rare-earth target, and they observed nearly identical slopes for 1- and 2-neutron transfer, contrary to simplest expectation that the 2-neutron slope should be twice that of the 1-neutron transfer.

F.W.N. de Boer *et al.*⁴ at GSI have bombarded ^{232}Th with ^{206}Pb and observed the 1- and 2-neutron transfer out of thorium.

Let us look at some recent data⁵ on primary populations in a one-neutron transfer reaction of a heavy deformed nucleus, namely, ^{58}Ni on ^{161}Dy . The odd neutron is in the $5/2^+ [642]$ Nilsson orbital, plotted in Fig. 1. From the NaI-ball at Oak Ridge the total gamma multiplicity and total gamma energy in coincidence with particular Ge(Li) resolved gamma lines were obtained. Fig. 2 shows a contour plot of the deduced primary population density going

into ^{160}Dy for the pick-up reaction on ^{161}Dy and the 2-neutron pick-up from ^{162}Dy . They show generally a "cool" process, with population concentrating at or slightly above the yrast envelope for lower spins and tailing to several MeV excitation at the highest spins. That the population contours smear below the yrast line is a reflection of the finite resolution of the system.

The pattern seen in Fig. 2 can be understood in simple terms. In Fig. 3 we show the total energy of the initial system $^{58}\text{Ni} + ^{161}\text{Dy}$ with ^{58}Ni in its ground state and ^{161}Dy on its yrast line, and the final system $^{59}\text{Ni} + ^{160}\text{Dy}$ with ^{59}Ni in its ground state and ^{160}Dy on its yrast line. The transfer is most likely to occur near the point of closest approach. A reasonable estimate of the average angular momentum at the turning point for the ^{161}Dy is $I^\pi \sim 17/2^+$. A cranked shell model calculation indicates that the $\Omega = 5/2^+$ unpaired particle is carrying ~ 4 units of aligned angular momentum for this state. Thus, an average value of the core angular momentum is ~ 4 at transfer. We assume the transfer of the particle to be a first-order process, so the transfer must proceed to states in ^{160}Dy which also have ~ 4 units of core angular momentum.

Two general functions limit the regions which the transfer from the $^{161}\text{Dy } 17/2^+$ state can populate in Fig. 3. First, there is a Q-window which favors population of a horizontal band centered at the energy of the $17/2^+$ state. This window is ~ 5 MeV wide and approximately Gaussian. Second there is a binding energy effect. The removal of more tightly bound particles from ^{161}Dy requires penetration of a larger barrier. This yields a factor decreasing exponentially in the square root of the separation energy of the transferred neutron. We show as contours in Fig. 3 the product of these two factors for a transfer assumed to proceed from the $^{161}\text{Dy } 17/2^+$ state. They conspire to force transfer to states lying relatively near the ^{160}Dy yrast line. Once the transfer is made, then the final nucleus ^{160}Dy may receive further collective excitation, provided the state populated is in a collective band.

Particle-rotor calculations⁶ suggest that for $i_{13/2}$ orbits the pickup of a single neutron from ^{161}Dy will

Fig. 2. Contour plots of the primary population density going into ^{160}Dy , for the 1-neutron pick-up reaction on ^{161}Dy and 2-neutron pick-up from ^{162}Dy . The abscissa is the "fold" or raw gamma multiplicity. Preliminary Monte Carlo corrections show for this case that "fold" and multiplicity are about the same in the region of the peaks. XBL 853-1567

Fig. 3. Evolution of the one-neutron transfer on the E vs. I plane. For details see the text. XBL 853-1568

have largest spectroscopic factors for the maximally aligned states. This would also tend to force the 2QP population to the right in Fig. 3. However, the calculations of ref. 6 assumed a strong-coupled ^{161}Dy state, and they should be repeated to assess the importance of alignment on that orbit in the present context.

Based on these ideas we offer the following interpretation of Fig. 2: The peak at lower multiplicity corresponds primarily to direct transfer to the ground band of ^{161}Dy , with the ^{59}Ni left in its ground state or low-lying excited states. The larger peak near multiplicity 6 and just above the ^{160}Dy yrast line represents strong population of low-lying 2QP states in the transfer, with Ni left in low-lying states. These states have large alignments, since a least one of the quasiparticles is in the orbit arising from the $\Omega = 5/2$, $i_{13/2}$ orbit. The addition of the angular momentum associated intrinsically with the transfer to aligned states accounts for the multiplicity (spin) gap between the lower and upper peaks.

Now consider 2-neutron transfer. Fig. 2 shows a superposition of the total energy and multiplicity plots for the reactions $^{161}\text{Dy}(^{58}\text{Ni}, ^{59}\text{Ni})^{160}\text{Dy}$ and $^{162}\text{Dy}(^{58}\text{Ni}, ^{60}\text{Ni})^{160}\text{Dy}$ (ref. 5 and unpublished). An approximate Dy yrast line assuming no excitation of Ni is shown.

It is immediately clear that both distributions display the same general features: a secondary maximum near multiplicity ~ 3 (that this is a maximum is more apparent in the unfolded spectrum. Fig. 2 shows the similarity for one- and two-neutron transfer of a primary maximum at larger multiplicity, and a distribution with most of the population within 2–3 MeV of the yrast line. However, there are also obvious differences between the two. The 2-particle transfer distribution peaks at higher multiplicity and total energy and exhibits a tail of events extending to even higher multiplicity and total energy.

We interpret the 2-particle distribution in a similar manner as in the 1-particle case.

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Heavy Ion Peripheral Collisions at Relativistic Energies: Theory of Giant Quadrupole Excitation*

J.O. Rasmussen, L.F. Canto,[†] and X.-J. Qiu[‡]

Introduction

In the study of heavy ion projectile fragmentation at GeV energies Heckman and Lindstrom¹ gave convincing evidence for two-step fragmentation involving the giant electric dipole resonance as intermediate. Earlier the question was raised about similar participation of the isoscalar giant electric quadrupole resonances as intermediates.²

It is not straightforward to apply optical-model methods, since nucleus-nucleus potentials are uncertain at these high energies. On the other hand, impulse approximation methods become more reliable at high energies, even for giant resonance modes.

We were stimulated by the "soft-spheres" model formulation of Karol³ in which he relates heavy ion reaction cross sections to nucleon-nucleon cross sections. In the present work we generalize that approach by including effects of deformation and apply it to inelastic scattering to collective states. The effects of the real part of the optical potential are included in our calculations. A comparison with predictions of a strong absorption model² is also made.

For the multipole collective excitation of colliding nuclei the multipole excitation cross section can be expressed in terms of the transition amplitude of the S-matrix

$$\sigma_\lambda = \int db \frac{d\sigma_\lambda(b)}{db} = \int db 2\pi b \langle f | S(b) | i \rangle^2 \quad (1)$$

where λ indicates the multipolarity of the excitation and where the $\langle f$ and $|i\rangle$ represent the final and initial states, respectively.

The soft spheres model for deformed nuclei.

In this section we evaluate the cross section σ_λ via the S-matrix within an optical model approach. As is well known, the single-particle optical potential may be given in the following form:⁴

$$U_{\text{opt}}^{\text{NA}}(\vec{x}) = t_{(E)}^{\text{MN}} \rho_1(\vec{x}) \quad (2)$$

where $t_{(E)}^{\text{NN}}$ denotes the forward ($\theta=0^\circ$) transition matrix for free nucleon-nucleon collisions at energy E and $\rho_1(\vec{x})$ the density of the nucleus at position $\vec{x}$.

For nucleus-nucleus collisions the optical potential can be derived by folding the nucleon-target potential (eq. (2)) with the density of projectile:

$$U_{\text{opt}}(\vec{x}) \equiv U_{\text{opt}}^{\text{A}_1\text{A}_2}(\vec{x}) = t_{(E)}^{\text{MN}} \int \rho_1(\vec{x} - \vec{x}') \rho_2(\vec{x}') d\vec{x}' \quad (3)$$

The free nucleon-nucleon transition matrix $t_{(E)}^{\text{NN}}$ can be derived from experiment. The imaginary part of $t_{(E)}^{\text{NN}}$ is given in terms of the total nucleon-nucleon cross section by the optical theorem, and its magnitude can be estimated by extrapolating the differential elastic cross-section to the forward direction.^{5,6} It can be written

$$\begin{aligned} t_{(E)}^{\text{NN}} &\equiv - \frac{4\pi\hbar^2}{2\mu} f(\theta=0^\circ) \\ &= - \frac{i\hbar v}{2} \sigma_{\text{NN}}^{\text{TOT}}(E) [1 - i\phi_{\text{exp}}(E)] \end{aligned} \quad (4)$$

where $\sigma_{\text{NN}}^{\text{TOT}}$ is the total cross section for free nucleon-nucleon collisions, v is the relative velocity, μ is the reduced mass, and $\phi_{\text{exp}}(E)$ is the ratio

$$\phi_{\text{exp}}(E) = \text{Re}[f(\theta=0^\circ)/\text{Im}(f(\theta=0^\circ))] \quad (5)$$

determined experimentally.⁵

The inclusion of the factor $[1 - \phi_{\text{exp}}(E)]$ in eq. (4) leads to a complex t -matrix, in contrast to the purely imaginary one of ref. 3. The optical potential of eq. (3) will produce, therefore, both absorptive and refractive effects in the nucleus-nucleus collision. The complete derivation and equations are too lengthy to reproduce here but are to be found in the full report.

Blair's strong absorption model for deformed nuclei.

A simple expression for the GQR cross section, based exclusively on the diffractive aspects of the collision, is given in the strong absorption model for deformed nuclei.² The cross section for the excitation of a collective state of multipolarity λ can be approximated by²

$$\sigma_{\lambda} = \frac{(B \beta_{\lambda})^2}{12} \left(\frac{B}{d} \right) \left[1 + (A_{\text{spec}}/A_{\text{exc}})^{1/3} \right]^{-2} \quad (6)$$

where B and d appear in the parametrization of the absolute value of the elastic S-matrix;

$$S_0(b) = \frac{1}{1 + \exp\left(\frac{B - b}{d}\right)} \quad (7)$$

and β_{λ} is the multipolarity λ zero point amplitude for the nucleus being excited.

To make a meaningful comparison with the results of the previous section we determine B and d by the condition that eq. (7) be consistent with the soft spheres "elastic" S-matrix of the preceding section, in the relevant range of impact parameters.

Numerical Results

To span the Bevalac energy range we have made calculations at energies of 0.5, 1.0, and 2.1 GeV/nucleon. We took parameters of the nucleon-nucleon scattering amplitudes from high energy N-N scattering and reaction tables.⁵ The empirical reduction factor of 0.52 for effective nucleon-nucleon cross sections is used in most cases, as shown.

Satchler⁷ has given the following expression for the zero-point amplitude β_L of a single state which would exhaust the sum rule:

$$\beta_L^2 = L(2L + 1) \left(\frac{\hbar^2/2mR^2}{\hbar W_L} \right) \frac{4\pi}{3A} \quad (8)$$

We have used this expression to get the β_{GQR}^2 values for our calculations. These values are listed in Table I.

Table II shows calculated GQR excitation cross sections (mb) for both projectile and targets. These are calculated both with the shape vibrating soft spheres expression and with the Blair diffraction expression [eq. (4)]. All of the calculated values in Table II were calculated with the nucleon-nucleon total cross section reduced by the factor 0.52 (c.f.

refs. 8-10). Columns 6 and 9 of Table II give the ratio of Coulomb excitation to nuclear excitation by an expression derived in the next section.

A comparison between columns 4 and 5 of Table II and between columns 7 and 8 shows that the simple strong absorption formula [eq. (6)] provides a reasonable estimate for the soft spheres GQR cross section except for projectile excitation of ^{12}C and ^{16}O , where there is nearly a factor of two disagreement.

An estimate of the soft spheres GQR cross section is thus given by the expression

$$\sigma_{\text{GQR}(T)} \approx 1.9 \cdot \beta_{\text{GQR}(T)}^2 \cdot (A_T^{1/3} + A_p^{1/3}) A_T^{2/3} \quad (9)$$

and similarly for projectile excitation with subscripts reversed.

Conclusions

An original motivation of this theoretical study was to determine a possible special role for giant quadrupole excitation in relativistic C and ^{16}O beam fragmentation, as measured spectrometrically by Olson, *et al.*¹¹ From Table II, column 4 we read a cross section of 37 mb for GQR excitation in ^{16}O by collision with Ag. If we assume a major decay mode for the ^{16}O GQR is alpha emission, then the GQR could contribute a third of the measured total ^{12}C yield of 104 ± 18 mb. Our calculated GQR cross section is close to that estimated by Rasmussen, Blair, and Qiu² from excess of ^{12}C yield over that calculated from abrasion-obliteration model.¹² The GQR excitation should be measurable in coincidence experiments with incident ^{16}O , by detecting both ^{12}C and ^4He and measuring their momenta.

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Table I: Values for β_{GQR}^2 used in our calculation (from Satchler⁷)

Nucleus	¹² C	¹⁶ O	¹⁰⁷ Ag	¹⁸⁴ W	²⁰³ Pb	²³⁸ U
β_{GQR}^2	0.33	0.23	0.018	0.009	0.008	0.006

Table II: Calculated Cross Sections for Excitation of GQR in Heavy-Ion Collisions

Projectile	Target	E/A(GeV)	GQR in Projectile (mb)			GQR in Target (mb)		
			$\sigma_{softsp.}^N$	σ_{Blair}^N	(σ^2/σ^N)	$\sigma_{softsp.}^N$	σ_{Blair}^N	(σ^C/σ^N)
¹² C	¹⁰⁷ Ag	2.1	42	23(23)	0.047	5	5(5)	0.20
	¹⁸⁴ W	2.1	52	27(27)	0.073	4	5(5)	0.47
¹⁶ O	¹⁰⁷ Ag	1.0	37	20(20)	0.083	6	6(6)	0.30
		0.5	32	20(20)	0.083	5	5(6)	0.30
	¹⁸⁴ W	2.1	46	24(22)	0.15	4	5(4)	0.77
	²⁰⁸ Pb	1.5	48	26(23)	0.17	4	5(4)	0.93
	²³⁸ U	1.0	51	26(26)	0.19	3	4(4)	1.2
¹⁰⁷ Ag	¹⁶ O	1.0	11	9(7)	4.8	11	9(7)	4.8
		0.5	10	9(7)	4.8	10	9(7)	4.8
	²³⁸ U	1.0	15	11(8)	12	6	6(5)	21
		0.5	13	10(8)	12	5	6(5)	21

Macroscopic Response of the Nuclear Surface*

V.I. Abrosimov[†] and J. Randrup[‡]

The nuclear surface region is probed in a variety of experiments, particularly inelastic scattering of hadrons to forward angles. The associated low momentum transfer explores the collective response of nuclei to external fields. We wish to understand the average behavior of the nuclear response on the basis of the macroscopic nuclear properties. For this purpose it is advantageous to consider the surface of a semi-infinite system, which is void of the many complications arising from the finiteness of real nuclei. For the relatively low values of the momentum transfer in which we are presently interested we may employ the Landau semiclassical theory of Fermi liquids.¹

We first consider the free surface oscillations of a semi-infinite Fermi liquid described by the Landau semi-classical theory. By employing the method of Fourier transforms, and invoking the appropriate boundary conditions, it is possible to devise a general dispersion relation. Specializing to modes with purely imaginary frequency ω , we find that

$$\omega = -i \frac{\sigma k_{\perp}^2}{\frac{3}{4} \rho_0 P_F} \quad (1)$$

Here $k_{\perp}$ is the wave number of the imposed surface wave, σ is the specific surface energy, ρ_0 the nuclear matter density and P_F the associated Fermi momentum.

The above mode is then simulated by a standard damped harmonic oscillator. Its stiffness $C_{k_{\perp}}$ is obtained by calculating the additional surface energy generated by ripples of wave number $k_{\perp}$, $C_{k_{\perp}} = \frac{1}{2} \sigma k_{\perp}^2$. Furthermore, the friction coefficient $\gamma_{k_{\perp}}$ is obtained by applying the one-body dissipation theory (the wall formula).³ $\gamma_{k_{\perp}} = \gamma_{wf} = \frac{3}{4} \rho_0 P_F$ (independently of $k_{\perp}$). With the above dispersion relation (1), we then find

$$\text{Im } \omega = - \frac{C_{k_{\perp}}}{\gamma_{k_{\perp}}} = - \frac{\omega_0^2}{2\lambda} \quad (2)$$

where $\omega_0^2 = C_{k_{\perp}}/B_{k_{\perp}}$ is the square of the undamped eigenfrequency and $\lambda = \gamma_{k_{\perp}}/2B_{k_{\perp}}$ is the damping decrement. Moreover, the inertial mass parameter is given by

$$B_{k_{\perp}} = \frac{\gamma_{k_{\perp}}^2}{4C_{k_{\perp}}} = \frac{\gamma_{wf}^2}{2\sigma k_{\perp}^2} \quad (3)$$

The relation (2) implies that the surface oscillator is critically damped.

The response function for the macroscopic surface motion can be obtained by invoking its relationship with the energy dissipation rate, yielding the result

$$R(\omega_{\text{ext}}, k_{\perp}) = \frac{4\sigma^2 k_{\perp}^2}{\gamma_{wf}^3} f_0 \frac{\omega_{\text{ext}}}{(\omega_{\text{ext}}^2 + \omega_0^2)} \quad (4)$$

where ω_{ext} is the frequency of the applied external field sustaining the surface motion.

Tentative application of these results to inelastic scattering of high-energy protons off heavy nuclei reproduces qualitatively the observed decrease in response with increasing energy, but a more exhaustive study is needed before a quantitative comparison will be informative. Generalization to spin-isospin dependent surface modes is an obvious and interesting direction for future development.

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An Analysis of Angular Momentum Projected Hartree-Fock-Bogoliubov Wave Functions in Terms of Interacting Bosons*

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Angular momentum- and number-projected Hartree-Fock-Bogoliubov (HFB) wave functions of transitional and deformed rare earth nuclei are analyzed in terms of Fermion pairs coupled to angular momenta $L = 0(S), 2(D), 4(G), \dots$. The Fermion space is truncated to contain only S-D or S-D-G pairs. The variation is carried out before and after angular momentum projection and also with different truncations. The influence of the truncation on physical quantities such as moments of inertia, quadrupole moments or pair transfer matrix ele-

ments is discussed.

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Fluctuations and the Nuclear Meissner Effect in Rapidly Rotating Nuclei*,[†]

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We here investigate the phase transition from a superfluid system to a normal fluid system in nuclei under the influence of a strong Coriolis field by the Generator Coordinate Method (GCM). The method allows us to take into account fluctuations of the orientation in gauge space connected with the violation of number symmetry in the BCS approach as well as fluctuations of the gap parameter connected with a virtual admixture of pairing vibrations in the wave function at the yrast line. The strange behavior of the experimental moments of inertia in the nucleus ^{168}Hf is well reproduced in this theory. The pairing collapse of the neutrons, however, is completely washed out by the fluctuations.

Mottelson and Valatin¹ predicted that under the influence of a strong Coriolis field in rapidly rotating nuclei the superfluid behavior of heavy nuclei should disappear, and a sharp phase transition to a normal fluid should occur.

Many attempts have been made to see this transition experimentally. Most of them were devoted to a search for anomalies in the rotational spectra,

which can be measured by (HI,xn) reactions with great accuracy. In fact, one has found anomalies such as the backbending phenomenon,² but it was soon realized that this phenomenon could be attributed not to a pairing collapse but to a sudden alignment of one pair of nucleons with large single particle angular momenta.³ In cases of alignment, quasiparticle energies can vanish while pairing correlations remain strong because the pairing field in such a situation is no longer diagonal. One then has nuclear gapless superconductivity⁴ and in such a situation it is difficult to observe the still existing superfluidity from the spectrum. In fact, after a few alignments one can assume to a first approximation that the quasiparticle energies are distributed statistically, a situation which causes the moment of inertia to be close to the rigid body value. Model calculations⁵ show that this occurs even for a constant pairing field.

In this paper we use a method which goes essentially beyond the mean field approximation, the Generator Coordinate Method. It yields in many

cases the exact solution,⁶ and it has the general advantage of being based on a variational principle. In particular it contains the mean field and the random phase approximation as limiting cases. The conclusions we can draw from such a calculation are therefore more general. The disadvantage of the method is that it is numerically rather demanding and thus requires a considerable computational effort. Details of the computation are to be found in our full report, from which this was condensed. Recent experiments in Daresbury⁷ have found for a number of nuclei in the Hf region a very constant value for the moment of inertia above spin $20\hbar$, close to the rigid body value. It has been suggested that this behavior signifies a sudden pairing collapse at spin $20\hbar$. In this letter we will concentrate on the case ^{168}Hf . In Fig. 1 we compare moments of inertia obtained in four different theories with the experimental values. The lower part shows mean field theories, namely simple HFB and number projected HFB, the upper part shows two versions of the GCM method. In one case we used simple HFB functions as generating functions; in the second case we used number projected HFB functions.

In Fig. 2 we show the GCM "wave functions". Since the GCM basis states are neither orthogonal nor linearly independent, the weight functions are not uniquely determined by the Hill-Wheeler equation.⁶ In particular they depend on the discretization procedure. We therefore show in Fig. 2 the "covariant components" of the GCM representation, the overlap integrals

$$\phi(\Delta) = \langle \Phi(\Delta) | \Psi \rangle \quad (1)$$

They measure the probability of finding a basis state $\Phi(\Delta)$ or $P^N \Phi(\Delta)$ in the GCM function Ψ . We also plot the collective potential in the rotating system

$$V(\Delta) = \langle \Phi(\Delta) | P^N (H - \omega J_x) P^N | \Phi(\Delta) \rangle \quad (2)$$

It is given by the diagonal element of the Hamilton kernel in the Hill-Wheeler equation.^{8,9} Using the parameter Δ as a classical coordinate this quantity is just the potential energy for a classical Hamilton function describing the collective motion in the pairing degree of freedom.^{10,11}

Fig. 1. Moments of inertia at the yrast line in ^{168}Hf . The experimental values of ref. 7 (full triangles) are compared in the lower part with mean field approximations and in the upper part with calculations based on the GCM method. For the dashed lines no number projection has been used. Full lines represent calculations with number projection. No core moment of inertia has been used.

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Fig. 2. GCM "wave functions" $\phi(\Delta)$ and energy surfaces for two angular velocities in the nucleus ^{168}Hf . Both quantities are given as functions of the generator coordinate Δ , the pairing deformation of the underlying unprojected HFB function. The "wave functions" are defined in eq. (1). The energy surfaces $V(\Delta)$ correspond to the rotating frame. Dashed lines correspond to calculations without number projection. Solid lines include exact number projection.

XBL 854-11066

There has been much discussion about how to define the gap parameter in theories going beyond the HFB approach. We use the definition

$$\tilde{\Delta} = G_0 \lambda \overline{\langle S^+ S \rangle} \quad (3)$$

In Fig. 3 we show this effective gap parameter for different theories as a function of the angular momentum: In HFB theory we observe a pairing collapse at $I = 22\hbar$. In all theories which go beyond this simple mean field approximation this sharp phase transition is smeared out. Surprisingly, there is little difference between the method of number projection before variation, which takes into account fluctuations in the gauge angle but neglects the virtual admixtures of pairing vibrations, and the full GCM theory with number projection. This result seems to indicate that the most important fluctuations for a proper description of pairing in nuclei are those treated in the symmetry conserving mean field theory. Additional correlations coming from virtual admixtures of pairing vibrations seem to play only a minor role.

Summarizing the results of these investigations, we must conclude that the sharp pairing collapse found in many HFB calculations for high angular velocities is completely washed out if one includes

Fig. 3. Effective gap parameters defined in eq. (3) as a function of the angular momentum I . At $I = 0$ all theories show the experimental values of Δ . This has been achieved by a minor adjustment of the strength parameter G_0 in each calculation. Broken lines correspond to a calculation without number projection; the solid line includes exact number projection.

XBL 854-11060

fluctuations. In particular we see that the surprisingly constant moments of inertia near rigid body values in several nuclei in the Hf region for spins above $20\hbar$ by no means are any indication for a pairing collapse. The situation of a sharp phase transition was shown earlier by number-projected HFB theory.⁵ From the present work this situation is not changed when we go a step further and include in addition fluctuations caused by pairing vibrations in the framework of a Generator Coordinate Method.

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On the Validity of the Mean Field Approach for the Description of Pairing Collapse in Finite Nuclei^{*,†}

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The transition from the superfluid to the normal phase in nuclei with increasing temperature and angular velocity is investigated within various approximations and in an exactly soluble model. It is found that the simple mean field theory always predicts a sharp phase transition, as for infinite systems. In theories taking into account fluctuations this sharp collapse is dramatically changed. In some cases no phase transition is observed.

In analogy to the superconductor in which one observes a phase transition to a normal conductor for a sufficiently high magnetic field and for increasing temperature, it has been predicted that for nuclear superfluidity an overall pairing collapse at higher angular momenta¹ should take place together with the breaking of individual pairs by the Coriolis force. Also, such collapse has been suggested to occur for higher temperatures,² in which the increasing excitation energy allows the population of unpaired configurations. So far these phase transitions in nuclei have not been experimentally observed, but calculations in simple models^{3,4} and in realistic nuclei⁵ have shown that indeed within the cranked Hartree-Fock-Bogoliubov (HFB) formalism a sharp transition to a normal fluid phase occurs at higher angular velocities. Similarly, one has found a pairing collapse with increasing temperature in model⁶ and in realistic calculations.⁷⁻⁹ In all these studies simple minded mean field theory (BCS¹⁰ or HFB) has been applied.

It is well known that the mean field approximation breaks down in the region of a phase transition, where fluctuations become important. The simple BCS or HFB approach, therefore, is expected to fail at high angular velocities and at temperatures where the pairing correlations become small.

In this work we investigate the validity of the mean field approach in the two cases:

1) at zero temperature and with increasing angular velocity

2) at zero angular velocity and with increasing temperature.

To go beyond the mean field approach, i.e., beyond cranked HFB, one has to take fluctuations into account. In our case the important correlations are connected with the pairing degree of freedom. In particular, the orientation of the BCS function in gauge space is fixed. To take these fluctuations into account self consistently we carry out a variation after projection on particle number.

The configuration space and the residual interaction of Baranger and Kumar¹¹ was used, and the unprojected self-consistent cranking (SCC) as well as the particle-number-projected (PNP) energy surface in the rotating frame was minimized by general HFB functions.⁵ The gap parameters Δ_p and Δ_n shown in the figure are obtained in both cases from the pairing energy:

$$\Delta_r = G_r \cdot \sqrt{\langle P_r^+ P_r \rangle} \quad (1)$$

where G_r is the pairing force strength and P^+ creates a Cooper pair coupled to angular momentum zero.

In Fig. 1 we show the results of the calculations for ¹⁶⁸Yb. The gap parameter for neutrons is rather low at spin zero and vanishes quickly in the unprojected SCC theory. At $I = 20\hbar$ we find a sharp neutron pairing collapse. This is connected with a smooth alignment of a $\nu_{13/2}$ pair. In the number-projected calculation the neutron gap does not vanish. It is reduced in the region of alignment, which corresponds to a transition to a blocked two-quasiparticle state. However, for all higher angular momenta it falls very slowly.

It is certainly interesting to study what happens to the predicted pairing collapse induced by temperature in calculations based on the mean field approach,⁷⁻⁹ when one includes additional fluctuations. At finite temperatures we have two kinds of fluctuations, quantal fluctuations, which are already

important at $T=0$, and thermal fluctuations. We investigate in the following first only the thermal fluctuations in the realistic case. Finally we discuss an exactly soluble model, which includes as well quantal as thermal fluctuations.

Treating the pairing gap as a collective coordinate one can derive a classical Hamiltonian function in the framework of adiabatic time dependent Hartree-Fock theory

$$H(p_\Delta, \Delta) = \frac{1}{2B(\Delta)} p_\Delta^2 + V(\Delta) \quad (2)$$

The potential $V(\Delta)$ is given by the temperature dependent mean field energy, and the mass parameter $B(\Delta)$ is for separable forces equal to the cranking mass.

Using the Hamiltonian function (2) we can calculate the probability $p(\Delta)$ that the nucleus has the gap Δ ,

$$p(\Delta) \propto \sqrt{B(\Delta)} \exp(-F(\Delta)/T) \quad (3)$$

where $f(\Delta)$ is the free energy obtained from $V(\Delta)$.

Neglecting the Δ dependence of the mass, one then ends up with a method used by Moretto¹² and Goodman¹³ for model cases. We take the Δ dependence of the mass-parameter into account and apply this method to a realistic case, namely, the nucleus ^{168}Yb . In Fig. 2 we show the mean field value for the gap and the average gap:

$$\bar{\Delta} = \int_0^\infty p(\Delta) \Delta d\Delta \quad (4)$$

We see, that, as expected, the sharp pairing collapse at $T = 0.5$ MeV is considerably smeared out by classical thermal fluctuations. We also find, however, that neglecting the Δ dependence of the mass (dashed line) emphasizes this effect somewhat. In fact, large pairing correlations decrease the mass parameter, making it less probable for the system to stay in regions of large pairing.

In order to study the influence of correlations in an exactly soluble model we use a single j shell, which is filled by N particles interacting via a monopole pairing force:

$$H = -G P^\dagger P \quad (5)$$

Fig. 1. Gap parameters Δ as defined in eq. (1) for the nucleus ^{168}Yb as a function of the angular momentum I at zero temperature: full lines correspond to neutrons, dashed lines to protons. Self consistent cranking (SCC) is compared with exact number projection before the variation (PNP). XBL 851-801

Fig. 2. The gap parameter for the nucleus ^{168}Yb as a function of the temperature at zero angular momentum. Δ is the gap parameter calculated in mean field theory (HFB). $\bar{\Delta}$ are average gap parameters as defined in eq. (4). In the full line the Δ dependent mass is taken into account, in the dashed line this mass is set constant. XBL 8411-6396

In the exact calculation the pairing gap is then expressed as

$$\Delta(T) = \sqrt{-GE(T)} \quad (6)$$

$E(T)$ being the correlation energy. In Fig. 3 this quantity is compared with the gap parameter $\Delta(T)$ in the temperature-dependent BCS approximation (lower curves) for various particle numbers N and different j values. We find in all cases that in the

mean field theory a sharp pairing collapse occurs at roughly $T_c = 0.2(j+1/2)G$. This collapse is smeared out in the exact calculation. However, we observe that the mean field theory provides a rather good approximation for large particle numbers and high j values, i.e., for high level densities.

Summarizing our results we find that a theoretical treatment of the pairing collapse going beyond the mean field theory shows the superfluid-normal phase transition can be smeared out considerably in finite nuclei. For the case of pairing collapse driven by the angular velocity at zero temperature a realistic calculation is possible and shows that the Mottelson-Valatin effect hardly exists in realistic nuclei. For the phase transition driven by temperature, classical calculations of the thermal fluctuations and exactly soluble models indicate that perhaps considerable pairing correlations may be expected at much higher temperatures than predicted by temperature-dependent HFB theory.

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Fig. 3. Pairing collapse in the single- j model of eq. (5) as a function of the temperature [in units of $(j+1/2)G$]. Different combinations of the level size j and the particle number N are shown. The lower curves are calculated in temperature dependent BCS approximation, the upper curves are exact results [eq. (6)]. We also indicate the exact gap for infinite temperature.

XBL 851-800

A Microscopic Description of Boson and Fermion Alignment in Octupole Bands of Actinide Nuclei^{*,†}

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The rotational alignment of the octupole boson in negative parity bands of Actinide nuclei is investigated in the framework of Cranked Random Phase Approximation (CRPA).

Modern heavy-ion accelerators allow us to study the behavior of rapidly rotating nuclei. A number of anomalous phenomena have been observed in this area, and it turned out that they can be explained as an interplay of collective and single particle degrees of freedom: Alignment phenomena of one or several particles caused by the strong Coriolis field of the rotating core give us the essential key for an understanding of these phenomena.¹

In most cases the alignment is caused by Fermions, namely neutrons or protons in intruder orbits with a large single particle angular momentum. On the other hand, collective nuclear excitations have also been described in terms of bosons. In negative parity excitations, which we concentrate on in this paper, octupole bosons play a crucial role. Most of the low-lying, low-spin, negative-parity states in heavy deformed nuclei have been described as collective octupole vibrations. Octupole bosons carry 3 units of angular momentum. In the Coriolis field of the rotating core they therefore feel a tendency to align, just as the single Fermions in the high spin intruder orbits.² In a pure boson picture one finds soon in going up the band a value of $3\hbar$ for the aligned angular momentum.^{3,4}

In real nuclei collective excitations consist, up to lowest order, of linear combinations of two-quasiparticle states. In a negative parity state, one of these Fermions sits in the high spin intruder orbit, i.e. in the Actinides in the $i_{13/2}$ orbit for protons or in the $j_{15/2}$ orbit for neutrons. It therefore experiences a strong Coriolis force, which tries to align it parallel to the rotational axis. At low spins this individual particle alignment is prevented by the relatively strong octupole correlations in the pair. It couples the two particles to spin $3\hbar$. With increas-

ing spin, however, the Coriolis force will become strong enough to break the 3^- pair, just as one Cooper-pair is broken in the backbending region. The question arises therefore, at which spin values this individual pair alignment will occur. Are the octupole correlations strong enough, to keep the octupole boson together up to spin values large enough that we can observe the rotational alignment of the boson, or does the octupole pair break already before this alignment is achieved? Recent experiments in the Actinides,^{5,6} where it is well known that octupole correlations are strong, show indeed in some cases first alignment of the boson and only later individual pair alignment.

The purpose of this paper is to present a unified microscopic theory for these complex alignment phenomena.

In the past several methods have been introduced to study the octupole bands in the Actinides,^{7,8} but these calculations present problems with the attenuation of the Coriolis force.

In the meantime Cranked RPA theory has been developed⁹⁻¹¹ and has been applied with great success for the description of rotational bands with positive parity.¹² In this paper we apply this method to negative parity bands in the Actinide region. At spin zero it corresponds precisely to the old RPA theory, which is very successful in the description of the band heads. For finite spins it treats the alignment mechanisms for bosons and fermions on the same microscopic level, and it is well known that the Cranking model has the proper amount of Coriolis attenuation.¹³

The CRPA formalism in the context of negative parity, as well as our model and the details of the computation, are to be found in the full report from which this was condensed. The general lines are the following:

In the first step the basis of the rotating shell model (RSM) is determined. We used for this pur-

pose the HFB-wave functions and the quasiparticle energies determined in ref. 14. There the RSM-equations are solved by the gradient method. We therefore have for each angular momentum at the yrast line I_{yrast} , the corresponding angular velocity ω .

In the second step we transform the octupole operators of the residual interaction to the rotating quasiparticle basis, where we perform the RPA with our octupole-octupole force. The theory is applied to the nuclei ^{232}Th , ^{236}U and ^{238}U .

In Fig. 1 the alignment pattern of the lowest band with negative parity ($K = 0^-$) for the different nuclei is shown. The theoretical aligned angular momentum i is the angular momentum component parallel to the rotational axis carried by the boson. It is given by

$$\begin{aligned} i_{\text{th}} &= \langle \text{RPA } B_\mu J_x B_\mu^\dagger \text{ RPA} \rangle \\ &- \langle \text{RPA } J_x \text{ RPA} \rangle \\ &= J_{\mu\mu}^{\text{II}} \end{aligned} \quad (1)$$

In Fig. 1 we show these values as a function of the cranking frequency. We also indicate the contributions coming from neutrons and protons. The three nuclei show a rather different behavior: in the two U-nuclei we first observe boson-alignment: a value close to $3\hbar$ is reached rather soon. The neutron contribution is definitely larger as the proton contribution, but for all angular velocities smaller than 200 keV no particle alignment is observed. In ^{232}Th the situation is different. For angular velocities smaller than 140 keV we observe an alignment pattern similar to the U-nuclei, but at an angular velocity of $\omega \approx 140$ keV the alignment increases strongly. The octupole-pair is broken and the proton in the $j=13/2$ shell decouples.

We also compare in Fig. 1 our theoretical results with the experiment.^{5,6} For the definition of the experimental alignment the yrast line was used as reference. A VMI-model was fitted to the low-lying members of the yrast line, and for constant angular velocity the experimental alignment is defined as the

Fig. 1. Aligned angular momentum i for the low lying negative parity band ($K=0^-$) in the nuclei ^{232}Th , ^{236}U and ^{238}U as a function of the cranking frequency. XBL 854-11100

difference between the full angular momentum and the VMI-value for the angular momentum of the yrast line. Although this definition of alignment is somewhat different from the theoretical alignment in Fig. 1, we still observe a good qualitative agreement in the alignment pattern for the three nuclei: In ^{232}Th particle alignment sets in very soon and boson alignment cannot develop. In ^{236}U and ^{238}U we see only boson alignment. Although we can reproduce these pattern rather nicely in our theory, we do not obtain quantitative agreement. As often observed in calculations,¹⁴ Cranking theory produces somewhat too much alignment.

In order to demonstrate even more clearly the different behavior of the $K = 0^-$ bands in these three nuclei we show in Fig. 2 to what extent the maximally aligned configuration ($i_{13/2}$ with signature $+i$ for the protons and $j_{15/2}$ with signature $-i$ for the

neutrons) are occupied in the "collective pair" obtained as the lowest solution of the RPA-equation. The quantities $\Sigma = \sum_k X_{kk}^{\mu}{}^2$ are displayed, $X_{\mu\mu}^{\mu}$ are the RPA-amplitudes of the one boson state and the index k runs over all levels in the $i_{13/2}$ orbit with signature $\pm i$ for the protons and overhauled levels in the $j_{15/2}$ orbit with signature $\pm i$ for the neutrons. We find a steep proton alignment in the nucleus ^{232}Th but nearly no individual particle alignment in the two other cases.

In conclusion, based on calculations within the Rotating Shell Model in ref. 14, which give a very satisfying description of the yrast configurations in Actinide nuclei, the Cranked RPA equations are solved for low lying negative parity bands in the three nuclei ^{232}Th , ^{236}U and ^{238}U . A separable octupole-octupole interaction is used, whose strength parameters are adjusted to the experimental band head energies.

We are thus able to describe in a unique microscopic framework the complicated interplay between collective degrees of freedom, with static multipole deformations and pairing, rotation and dynamic octupole vibrations on one side and the single particle degrees of freedom dominated by the large angular momentum of the intruder orbits on the other side.

In detail we observe in some cases rather strongly bound collective pairs, which align together as an octupole boson in the Coriolis field of the rotating core, in other cases the collective nature disappears rather soon. The octupole bosons break up, and we find the alignment of single particles in the intruder orbits.

Footnotes and References

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Fig. 2. Structure of the lowest lying RPA solution ($K=0$ band) as a function of the angular momentum for the three nuclei ^{232}Th , ^{236}U and ^{238}U . See text for more details. XBL 854-11102

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Temperature Dependent Hartree-Fock-Bogoliubov Calculations in Hot Rotating Nuclei^{*,†}

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Cranked temperature dependent Hartree-Fock Bogoliubov (CTHFB) equations in the rotating frame are solved numerically for a realistic case in the rare earth region, the nucleus ^{164}Er . The behavior of pairing correlations, shape degrees of freedom, and other physical quantities is discussed as a function of angular momentum and temperature.

Within the last few years an increasing number of experimental studies have been devoted to the investigation of highly excited compound states in nuclei formed after a heavy-ion fusion reaction. Two parameters characterize this region, the excitation energy and the angular momentum. A number of new features are expected, such as phase transitions and changes of the nuclear shape. The investigations in this work are devoted to the transition region between the discrete levels at the yrast line and the classical regime, where pairing correlations have vanished. This region is characterized by a steeply rising level density as a function of the excitation energy. It is therefore meaningless to describe this regime in terms of discrete bands. Since the lifetime of such a compound state is sufficiently large, we can assume that in this region of high level densities one has thermodynamic equilibrium, which allows us to describe the nucleus in this region by a statistical ensemble with a fixed temperature. As an additional approximation we use mean-field theory with constraints on the physically important quantum numbers as particle number and angular momentum, i.e., we use the Cranking model. Following all these arguments we use in this paper Cranked Temperature dependent Hartree-Fock-Bogoliubov (CTHFB) theory, and we apply it to a realistic case, the nucleus ^{164}Er , a typical example for a well deformed axially

symmetric heavy nucleus which shows relatively strong pairing at the ground state.

Temperature-dependent BCS and HFB theory was introduced many years ago.¹⁻⁴ For the description of a rotating nucleus, Cranked temperature dependent HFB theory is needed. It has been discussed in the framework of perturbation theory and in exactly soluble models.⁵ The first application to a realistic case in the framework of the cranking model was carried out by Tanabe, *et al.*^{6,7} It turned out that in cases of negative quasi particle energies, which occur in the region of band crossings, CTHFB theory does not give the proper limit for $T=0$, where one should find the usual Cranked HFB results. Tanabe *et al.* extended CTHFB theory by projecting onto good parity and onto good number parity. They thus obtain the proper limit for small temperatures. On the other hand, because of the increased numerical difficulties connected with this projection, additional approximations have been introduced for the solution of the variational equations. Therefore, the full CTHFB equations have not been solved so far for realistic heavy nuclei. In this paper we present such a solution. THFB theory has been described by many authors,⁵⁻⁸ and details of the calculations are to be found in our full report, from which this was condensed. For a realistic application of Cranked THFB theory we use the configuration space and the effective interaction of Kumar and Baranger.⁹

In Fig. 1 we show the internal energy for constant temperatures (isothermal lines) and for constant entropy (isentropic lines). The isothermal lines are more or less parallel to the yrast line. They increase for all temperatures monotonically with the

angular momentum. We do not find minima at finite low spins even for higher temperatures as they have been found in ref. 7; i.e., we do not find the new phase transition discussed in refs. 10, 11. We do not think that this different behavior, which shows up only at higher temperatures, is caused by the slight differences in configuration space and in the residual interaction. Nor is it caused by the projection onto good parity and number parity in ref. 7. We believe that the minima in Fig. 1 of ref. 10, which the authors understand as an indicator of a new phase transition called "bidirectional alignment," are caused by the approximation used in the numerical solution of the CTHFB equations. The isentropic lines behave to a great extent as the isothermal. Only for small angular momentum and small excitation energies are the slopes different. For all other values of E and I they are parallel.

In Fig. 2 we show the pairing gap parameters for neutrons (for protons it is similar) as a function of the angular momentum for different temperatures. We observe a pairing collapse as a function of the angular momentum as well as a pairing collapse as a function of the temperature. The critical angular momenta for zero temperature are $I = 30\hbar$ for the neutrons and $I = 50\hbar$ for the protons. The critical temperatures at zero spin are $T=0.5$ MeV in both cases. These two phase transitions have been discussed earlier in model calculations⁵ and in realistic nuclei,²⁻⁸ and the results obtained in this paper are more or less in agreement with these earlier investigations. In mean field theory, which is used in our calculations, these phase transitions are very sharp, as one expects in an infinite system. We have to keep in mind, however, that real nuclei are finite systems and in reality these transitions might be smeared out considerably by fluctuations.¹⁷⁻¹³

In Fig. 3 we show the deformation parameter β for the self consistent solution of the CTHFB equations as a function of the temperature. We study the region of $T \leq 1$ MeV. In this temperature region the nucleus ^{164}Er turns out to be very stiff against shape changes. With increasing temperature we find only very small changes in β ; there is only a small tendency to spherical shapes at the highest temperatures

Fig. 1. The energy of the nucleus ^{164}Er as a function of the angular momentum. Full lines are isothermal lines and correspond to constant temperatures (the units are MeV) with $T = 0.0, 0.1, 0.2, \dots, 1.0$, dashed lines are isentropic lines and corresponds to constant entropy with $S = 0, 5, 10, \dots, 30$. XBL 856-9559

Fig. 2. The gap parameter for the neutrons in the nucleus ^{164}Er as a function of the angular momentum for different temperatures (in units of MeV). For all temperatures $T \geq 0.5$ MeV the gap vanishes. XBL 8411-6386

Fig. 3. The deformation parameter β in the nucleus ^{164}Er as a function of the temperature for different angular momenta. XBL 8411-6397

under consideration, as one would expect in a classical picture. In the region of small spins ($I < 30\hbar$) we find at temperatures $T < 0.5$ MeV first an increasing deformation. This is clearly connected with the Coriolis-anti-pairing effect in this region. Increasing temperature decreases pairing, which in turn allows the nucleus to become more deformed. Such an effect is no longer seen for angular momenta beyond the pairing collapse.

At very small temperatures ($T < 0.1$ MeV) we observe for the higher spins a small kink. It has its origin in the fact that the smallest finite temperature for which we solved the CTHFB equations was $T = 0.05$ MeV. As discussed in the introduction there is no continuous connection to the calculation with $T = 0$.

For all temperatures under consideration the nucleus ^{164}Er is also relatively stiff against γ -deformations. For small temperatures we find increasing γ -values for increasing spin. This behavior has been observed in many calculations in this region.¹² It contradicts the classical picture, where one expects the nucleus to flatten more in the direction of the rotational axis, which would correspond to negative γ -values. This unexpected behavior is obvi-

ously connected with the shell structure, and we find that it disappears more and more with increasing temperature.

Finally for the moments of inertia $\mathcal{J}$ we found that for small temperatures and small spin values we have pairing correlations, which produce the well known reduction of $\mathcal{J}$ in this region. For $T > 0.5$ MeV pairing has collapsed and we find rather constant moments of inertia for all spin values, somewhat larger than the rigid body value. For small temperatures we find a steep increase of the moment of inertia between 10 and 20 $\hbar$. It is well known that it is connected with the sudden alignment of a $i_{13/2}$ pair of neutrons, which produces backbending at the yrast line.

The results obtained in this calculation are in qualitative agreement with earlier model calculations and in many points also in agreement with earlier non fully selfconsistent investigations⁸ and with work by Tanabe, *et al.*,⁷ where the CTHFB equations have been solved approximately. There are, however, some essential differences. In particular, we do not find any indication of the new phase transition called "bidirectional alignment" proposed in refs. 10 and 11.

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Bulk Compression Due to Surface Tension in Hartree-Fock, Thomas-Fermi and Droplet Model Calculations*

J. Treiner,[†] W.D. Myers, W.J. Świątecki, and M.S. Weiss[‡]

A number of recent studies have been devoted to the comparison between density distributions predicted by the Droplet Model of atomic nuclei and those predicted by Hartree-Fock calculations.^{1,2} Some of these studies raised questions about the validity of the Droplet Model approach for treating the neutron skin in neutron-rich nuclei and, in particular, about an elementary prediction of the Droplet Model concerning the squeezing of nuclei by the surface tension. While existing Hartree-Fock calculations were not sufficiently comprehensive to be able to settle these questions, certain features of the numerical results raised concerns over whether or not the Droplet Model was correctly formulated. The relation of the Droplet Model to Thomas-Fermi (rather than Hartree-Fock) calculations had been thoroughly investigated in the original Droplet Model paper³ and perfect agreement had been found as regards the neutron skin as well as the surface tension squeezing in the appropriate limit of sufficiently large nuclei, in which the Droplet Model should formally be valid. However, two questions still remained. First, does the change from a Thomas-Fermi to a Hartree-Fock treatment, in addition to bringing in the expected oscillations in nuclear properties associated with shell effects, also modify in some unsuspected way the *shell-averaged* behavior, thus invalidating the Droplet Model predictions of average nuclear properties?

Second, even if the Droplet Model predictions were found to be formally valid for sufficiently large hypothetical nuclei, are they *quantitatively* useful for actual nuclei throughout the periodic table?

To address these questions Hartree-Fock calculations for hypothetical spherical nuclei with $N = Z$ were carried out without the inclusion of Coulomb interactions, spin-orbit terms or pairing in order to study one simple property of such systems: the bulk compression due to surface tension. We found that the behavior expected from Thomas-Fermi and Droplet calculations manifests itself for medium and heavy nuclei, and the relation between microscopic and macroscopic descriptions was further illustrated by carrying the calculations to extremely large mass numbers.

In order to test the Droplet Model predictions we performed two sets of Hartree-Fock calculations, using two types of Skyrme interactions corresponding to two values of the incompressibility coefficient: $K = 355.6$ MeV for the Skyrme force S-III and $K = 216.6$ MeV for the Skyrme force SkM. In each case we determined the self-consistent Hartree-Fock density distributions for all closed-shell spherical nuclei with $N = Z$ and mass number A from 16 to 3112. (There was no spin-orbit force, so the shell closures do not correspond to those for actual nuclei.)

We made a least-squares fit of a smooth distribution to the radial Hartree-Fock density function, weighted with r^2 , and used the central value of the smooth density as a representation of the bulk density of the Hartree-Fock distribution. See Fig. 1.

Even with the fluctuations of the idealized Hartree-Fock calculations in Fig. 1 it is possible to discern systematic trends, which may be compared with the Droplet Model predictions, given by the straight line. For very large systems ($A^{-1/3} < 0.15$, i.e., $A > 300$) there is clear indication that the Hartree-Fock bulk densities are converging towards the nuclear matter value (i.e., $\Delta\rho \rightarrow 0$). This removes the misgivings one might have had (by looking only at the points for $A < 300$) that even this elementary expectation was not borne out by the numerical calculations. The prediction of the Droplet Model is, roughly speaking, consistent with the trend of the Hartree-Fock calculations for $A^{-1/3} < 0.15$. For lighter nuclei one can discern, despite the large fluctuations, a tendency for the average of $\Delta\rho/\rho_0$ to decrease, contrary to the Droplet Model prediction. We had already noted such a trend in the Thomas-Fermi calculations in ref. 3 and we found it again in Thomas-Fermi calculations with the same Skyrme forces. However, apart from shell fluctuations, there does not appear to be evidence for a fundamental disagreement between Hartree-Fock trends and Droplet Model predictions beyond those already noted in connection with Thomas-Fermi calculations.

Footnotes and References

* Condensed from LBL-18477

Fig. 1. The fractional deviation of the bulk density extracted from Hartree-Fock calculations using the force SkM is plotted against $A^{-1/3}$ for nuclei with $N = Z$ and with mass numbers from 16 to 3112. The straight line represents the lowest order Droplet Model prediction, the dot-dash curve a higher-order approximation, and the dashed curve Thomas-Fermi results.

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Droplet Model Electric Dipole Moments*

C.O. Dorso,[†] W.D. Myers, and W.J. Świątecki

Since there is considerable current interest in unusually fast E1 transitions in the Ra-Th region that seem to be associated with collective ground state dipole moments (and octupole deformations),¹ we performed a calculation of the macroscopic contribution to the dipole moment of a deformed (axially symmetric but reflection asymmetric) nucleus, using the Droplet Model. In addition to the familiar

charge redistribution effect (which is worked out including a correction for the relative neutron excess $(N-Z)/A$ and a second correction of relative order $A^{-1/3}$), the Droplet Model predicts a contribution from the presence of a neutron skin. This contribution turns out to be of the same order as the redistribution effect and of opposite sign. The result is a reduction of the macroscopic contribution to the di-

pole moment to small or even negative values, as compared with earlier estimates.^{2,3}

The dipole moment D , in units of the proton charge e , is found to be given by the following expression:

$$d = C_r \sum_{\ell=2}^{\infty} \frac{12(\ell-1)(\ell+1)(8\ell+9)}{5(2\ell+1)^2(2\ell+3)^2} \alpha_{\ell} \alpha_{\ell+1} - C_s \sum_{\ell=2}^{\infty} \frac{(\ell-1)(\ell+1)(\ell+3)}{(2\ell+1)(2\ell+3)} \alpha_{\ell} \alpha_{\ell+1} + \text{terms of higher order in the } \alpha_{\ell}'\text{'s} \quad (1)$$

Here α_{ℓ} are the coefficients specifying the usual Legendre Polynomial expansion of the radius vector $R(\theta)$, describing the surface according to

$$R(\theta) = R_0 \left[\sum_{\ell=2}^{\infty} \alpha_{\ell} P_{\ell}(\cos \theta) \right] \quad (2)$$

The coefficients C_r and C_s are definite functions of the neutron and proton numbers N, Z and of the equivalent radius R_0 of the nucleus in question, as well as of the relevant parameters specifying the volume energy per particle and the surface tension coefficient in the Droplet Model:

$$C_r = (AZe^2/8) \left[\frac{1}{J} + \frac{6L}{JK} I + \frac{15}{8Q} A^{-1/3} \right] \quad (3)$$

$$C_s = (2NZ/A)(1 - \bar{\delta})R_0 \quad (4)$$

where

$$\bar{\delta} = \frac{1 + (3c_1/16Q)ZA^{-2/3}}{1 + (9J/4Q)A^{-1/3}} \quad (5)$$

The first term in the bracket in eq. (3) is the same as that considered by Strutinsky² and Bohr and Mottelson.³

The inclusion of the neutron skin degree of freedom leads to a slight separation of the centers of mass of the neutrons and protons, resulting in another

contribution to the dipole moment. This influence of the neutron skin on the dipole moment does not appear to have been studied before. The effect is, in most cases of interest, of a magnitude comparable with the charge-redistribution effect (and of opposite sign!). This means that a meaningful estimate of the macroscopic part of the nuclear dipole moment cannot be made without taking into account the neutron skin contribution in addition to the charge redistribution effect.

Without being able at this time to make a closer analysis of the relation of the macroscopic theory to the experimental determinations of the dipole moments of nuclei, we hope that the relatively accurate Droplet Model expression for the macroscopic part, eq. (1), will be of help in improving our understanding of this aspect of nuclear structure.

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Finite Range Effects and Conditional Barrier Heights^{*,†}

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The experimental distinction between the processes of evaporation and fission in relatively heavy compound nuclei can be understood in terms of a specific topological feature in the liquid drop

model potential energy surface $V(Z)$ as a function of mass asymmetry Z . This feature is a deep minimum at symmetry (fission region) flanked at greater asymmetries by the Businaro-Gallone mountains which in

turn descend at even larger asymmetries ("evaporation" region). The corresponding mass distribution expected for compound nucleus decay is approximately proportional to $\exp[-V(Z)/T_0 Z]$, where T_0 is the temperature of the conditional saddle point, and indeed shows a peak at symmetry (fission peak) and two wings at the extreme asymmetries (evaporation wings).

In progressively lighter compound nuclei the potential energy surface undergoes a topological change as the fissionability parameter x crosses the Businaro-Gallone point. At this point the second derivative of the potential energy with respect to the mass asymmetry coordinate evaluated at symmetry vanishes. Thus below the Businaro-Gallone point there is no longer a true fission saddle point, and the monotonically increasing potential energy towards symmetry determines the disappearance of fission as a process distinct from evaporation. In other words the mass distribution should show the two evaporation wings extending as far as symmetry where a minimum should be observed.

Within this framework, it has been possible to describe, in a continuous way, the transition from light particle emission to fission.¹ This theory also predicts changes in the shapes of both the kinetic energy spectra and angular distributions of the emitted fragments as their masses increase from α -particles toward fission fragments. These predictions¹ are amenable to experimental test; unfortunately, there is a surprising lack of experimental data that can be compared with the above unified treatments or with more standard formalisms.

Complete excitation functions obtained from the ${}^3\text{He} + {}^{\text{nat}}\text{Ag}$ measurements are shown in Fig. 1 for a series of decay products. The measurements were restricted to the backward angles (120° - 160° in order to insure measurement of only the equilibrium component.

With increasing bombarding energy, the cross sections rise rapidly and then flatten at higher energies. This is a characteristic signature of compound nucleus emission. The cross section for $Z=3$ is a factor of 1000 lower than that for $Z=2$, and for the heavier fragments it is even lower. In spite of these

Fig. 1. Dependence of the total integrated cross sections for emission of complex fragments on the center-of-mass energy, $E_{c.m.}$ in the reaction ${}^3\text{He} + {}^{\text{nat}}\text{Ag}$. The points and error bars correspond to the experimental cross sections. The curves are fits with the parameters of Fig. 2. XBL 848-8658

low cross sections, we were able to measure an excitation function over 2-3 orders of magnitude up to $Z=11$, with a detection limit of about 50 nb.

The experimental excitation function data have been fitted using a transition state formalism, analogous to that used to fit fission excitation functions.¹ As shown in ref. 1, the decay width for first-chance emission of a fragment of charge Z can be written as

$$\Gamma_z = \frac{1}{2\pi\rho(E)} \int_0^{E-B_z} \rho_z^*(E - B_z - \epsilon) d\epsilon \quad (1)$$

where $\rho(E)$ is the compound nucleus level density, B_z is the conditional barrier height, and $\rho_z^*(E - B_z - \epsilon)$ is the level density at the conditional saddle with a kinetic energy ϵ in the decay mode. The neutron width Γ_n can be written as

$$\Gamma_z = \frac{2mR^2g}{2\pi\rho(E)} \int_0^{E-B_n} \epsilon\rho(E - B_n - \epsilon) d\epsilon \quad (2)$$

We make the assumption that the ratio of the decay widths, Γ_z/Γ_n , is proportional to the ratio of the cross section for complex fragment emission, σ_z , to that for complete fusion, σ_R , i.e.,

$$\Gamma_z/\Gamma_n \approx \frac{\Gamma_z}{\Gamma_t} \approx \frac{\sigma_z}{\sigma_t} \approx \frac{\sigma_z}{\sigma_R} \quad (3)$$

This is reasonable in this mass region because $\Gamma_n \gg \sum_{Z \geq 1} \Gamma_z$. One can then calculate $\Gamma_z/\Gamma_n(E)$ using an appropriate choice for the level density expression. A Fermi gas level was used because it gives an analytical expression for Γ_z/Γ_n . A simple angular momentum dependence has been included by adding to the barriers the rotational energies appropriate to the ground and saddle point deformations.

Using the above expression for Γ_z/Γ_n , the barriers B_z , and the ratio a_z/a_n , of the level density parameters were extracted from fits to the experimental data σ_z/σ_R . These fits are shown by the solid lines in Fig. 1. The agreement between the data and the fits is remarkably good for all Z -values and confirms that these products originate from compound nuclear decay.

The barriers extracted from the fits are shown by the circles in Fig. 2 as a function of Z . The extracted barriers increase dramatically as the exit channel becomes more symmetric. Some evidence of shell effects in the exit channel is visible in the barrier for carbon emission, $Z=6$, which is lower than those of the neighboring elements.

The barriers so obtained can be used to test modern corrections to the liquid drop model, like surface diffuseness and finite range, which become important for strongly indented saddle configurations like those presiding to the emission of complex fragments. A comparison of the standard liquid drop model prediction and of the model incorporating the corrections mentioned above² with our data is also shown in Fig. 2. Clearly our data strongly support the introduction of surface diffuseness and finite range. It is also easy to understand how these and similar data may be very valuable in fixing the relevant parameters of the model.

Similar results we have obtained up to 40 MeV/nucleon with the ^9Be target and with the Al target.

In the course of this work we have learned of a similar experiment at Ganil in which very similar results have been obtained.

The conclusions that can be drawn from these preliminary data are rather firm. The great majority of the complex fragments produced in these reactions is associated with a binary decay from a source with a large momentum transfer. All the indications point to a compound nucleus formed by the nearly complete fusion of Be and Nb which in turn decays by a binary process to yield complex fragments, much like what we saw at much lower energy.

Mechanisms like cold fragmentation or liquid vapor equilibrium are inherently higher multiplicity processes which are inconsistent with the observed binary decay. Consequently these mechanisms must be ruled out in the energy regime of our investigation and should be looked for at higher energy where, undoubtedly, the complex fragments will be associated with higher multiplicity events.

Fig. 2. The emission barriers, B_z , extracted in fitting the excitation emission of complex fragments functions as a function of fragment charge. The two lines correspond to calculations with the liquid drop model and with the inclusion of finite range effects.

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Shape-Dependent Finite-Range Droplet Model*

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A treatment of nuclear masses and deformations which combines the Droplet Model with the folding model surface and Coulomb energy integrals has been developed. It includes an additional exponential term, inspired by the folding model but treated here as an independent contribution with two adjustable parameters and a shell correction term taken from the work by Möller and Nix¹ in 1981. Nine parameters in the macroscopic part of the model were adjusted in the final fit to 1488 masses and 28 fission barriers. The resulting root-mean-square deviations for the masses and fission barriers were 0.676 MeV and 1.135 MeV, respectively. More complete details about the model are given in ref. 2.

In addition to the revised surface and Coulomb energy expressions with their corresponding dependences on shape and scale, the Finite Range Droplet Model (FRDM) contains the new exponential term,

$$-C A e^{-\gamma A^{1/3}} \quad (1)$$

with two new adjustable parameters C and γ . This type of exponential term, non-analytic in the Droplet Model expansion parameter $A^{-1/3}$, appears in the folding type expressions for the interaction energy.

The key to the substantially improved results we have obtained here seems to be the empirical exponential term of eq. (1). We had hoped that all the finite range effects would be adequately represented by the folding model surface energy expression, but this was not the case. Fig. 1 serves to illustrate this point. The quantity plotted here versus $A^{-1/3}$ is $(\Delta\rho/\rho_0)_{\text{bulk}}$, which is the fractional deviation of the central density of a nucleus from the nuclear matter value. For the idealized case of $N=Z$ nuclei without Coulomb energy the FRDM expression (with notation from ref. 2) is,

$$(\Delta\rho/\rho_0)_{\text{bulk}} = 6(a_2/K)A^{-1/3} - 3(C/K)e^{-\gamma A^{1/3}} \quad (2)$$

The solid line in the figure is the old DM prediction obtained by keeping only the first term. The dashed line illustrates the much more dramatic effect which is produced by including the second term in eq. (2).

The behavior of this complete expression corresponds very closely to that found in earlier Thomas-Fermi calculations (See Fig. 30 of ref. 3). It also corresponds quite closely to the behavior we have noted recently in studies of Hartree-Fock calculations.⁴ This is all the more remarkable when we recall that the coefficients of this new phenomenological term were determined solely from a least square fit to masses and fission barriers. No considerations regarding density distributions governed their determination.

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Fig. 1. Fractional deviation of the central density versus $A^{-1/3}$ predicted by the model for hypothetical uncharged nuclei with $N = Z$. XBL 848-3599

PART IV: INSTRUMENTATION AND METHODS

The 88-Inch Cyclotron ECR Source

C.M. Lyneis and D.J. Clark

The LBL ECR ion source began test operation in January 1984. A new axial injection line, which has improved beam optics and a much better vacuum than the old axial beam line, was completed in September 1984. Injection tests into the 88-Inch Cyclotron began in October, and regular operation with the cyclotron started in January 1985. Previous publications have described the design of the source and injection system and the initial source performance.^{1,2} A later paper³ describes the first operational experience and recent developments of the source and injection system.

The ECR source, injection beam line and cyclotron center region have performed reliably since coming into regular operation in January 1985. The nuclear physics groups have already become enthusiastic users of the new ECR beams. Operation of the ECR source and injection beam line requires about 100 kW of power. In some cases, the ECR source allows a higher charge state to be accelerated than did the internal PIG source. This results in a lower main cyclotron field and a net power savings. The long term stability over several days has been good, requiring only an occasional adjustment of the source.

The testing and development of the source, which began test operation in January 1984, is still continuing although the source is now largely dedicated to providing beam for the cyclotron. In its original configuration the second stage radial magnetic field was produced by a sextupole with an effective inner diameter of 80 mm. In June 1984 an octupole was installed to test the effect of using a higher multipole. The inner diameter of the octupole was 94 mm. The source performance was significantly improved by this change.⁴ In November, with the collaboration of the NSCL group at Michigan State University, a new large sextupole with the same inner diameter as the octupole was installed to determine whether the improvement was due to the increased chamber volume or the change of the multipole. The performance of the source with the large

sextupole was comparable to the performance with the octupole. It may be that the increased volume in the second stage allows for more efficient coupling of the RF power to the plasma, thereby raising the average electron temperature. This effect could be more significant in the LBL ECR because the operating frequency in the second stage is 6.4 GHz compared to 8.5 GHz and 10 GHz in other ECR ion sources. Another explanation for the improved performance with the larger radius chamber is the reduction of neutral pressure due to better plasma pumping. Since regular operation of the ECR source with the cyclotron began in January 1985 we have been operating the source with the large sextupole.

The installation in April 1985 of the new first stage resulted in a dramatic improvement in the performance of the LBL ECR. The O^{7+} current increased from 4 to 8 μA and Ar^{14+} from 130 to 730 nA. The new first stage made tuning the source easier and more reproducible and it improved the long term stability. The source recently ran for 4 days producing 50 μA of Ar^{9+} with no adjustment.

In Table I the performance of the LBL ECR source is summarized. All results are given for 12 mm analyzer slit widths and an extraction voltage of 10 kV except in cases such as $^{18}O^{8+}$ where narrower analyzer slits were used to improve the resolution. The currents represent the best results taken from many tests. Larger currents can be attained at higher extraction voltage.

With respect to operation of the source, the elements in Table I fall into three classes. First, elements available in gaseous form present no particular problems. Generally, they are injected into the first stage with an appropriate mixing gas. The second class are elements which occur as solids, but are available as gaseous compounds such as silicon and sulfur. The silicon beam was produced by injecting silane gas directly into the second stage of the source with oxygen used to maintain the first stage plasma.

Table I
Ion Currents of the LBL ECR Source

	N	O	Ne	Mg	Al	Si	S	Ar	Ca	Kr	Xe
1 ⁺	73.	100.									
2 ⁺	96.	117.	51.	32.	18.	20.					
3 ⁺	104.	125.	63.	34.	40.	33.	10.	38.	23.		
4 ⁺	76.	79.	78.	28.	60.	69.	*	40.	24.		
5 ⁺	64.	89.	58.	44.	43.	72.	20.	*	*		
6 ⁺	17.	82.	45.	34.	36.	47.	*	54.	37.	8	
7 ⁺	*	11.	16.	18.	22.	30.	63.	66.	38.	7.8	
8 ⁺		.37	6.5	8.	10.	17.	*	106.	36.	14.	
9 ⁺			1.1	6.3	*	7.0	36.	72.	31.	18.	.7
10 ⁺			.041	2.2	*	2.7	*	*	*	20.	.7
11 ⁺				.1	.065	0.5	5.0	18.	22.	20.	.66
12 ⁺						0.2	*	11.	11.	12.	.8
13 ⁺						.005	.40	3.3	2.4.	15.	.94
14 ⁺							*	.73	0.2.	10.	1.1
15 ⁺							.001	*	*	6.8	1.1
16 ⁺								.025	.005	4.2	1.4
17 ⁺										2.8	1.6
18 ⁺										1.5	2.0
19 ⁺										0.6	2.0
20 ⁺											2.2
21 ⁺											2.3
23 ⁺											1.8

All currents in μA at 10 kV extraction voltage. Feed materials had natural isotopic abundances.

*Indicates not measured because a mixture of two ions with identical charge to mass ratios were present.

The third class of elements are the metals. Some, such as aluminum, were run by direct insertion into the plasma.² Others, such as magnesium and calcium, used an oven. The open structure of the LBL ECR multipole allows for easy radial insertion of solids into the plasma and it also allows for ovens to be used for injecting metal vapor beams. Stable beams of magnesium and calcium were produced with ovens for periods of 24 hours.

The radial emittance of the ECR beam was measured with a scan cup, together with the analyzing magnet image slit. The divergence is approximately proportional to the width of the beam at the scan cup, which is 2 m downstream from the analyz-

ing slit. An example of scan data for oxygen beams is given in Fig. 1. Each charge state scan has a central core and a tail. The tail may be due to a high energy tail in the source plasma or aberrations in the extraction system. Fortunately the cyclotron injection system accepts most of the beam divergence, even for the low charge states. The beam emittance in the central core is in the range $20\text{--}110\pi \text{ mm} \cdot \text{mrad}$, increasing from high to low charge states. This variation with charge state is much larger than expected from a constant transverse plasma energy, which would give a $1/\sqrt{Q}$ dependence.

Injection of beams into the cyclotron uses the

Fig. 1. Beam current profiles across beam pipe, taken with scan cup, at 10 kv accelerating voltage. The beam intensities are: 1+ 16 μ A, 2+ 19 μ A, 3+ 27 μ A, 4+ 108 μ A, 5+ 46 μ A, 6+ 56 μ A, 7+ 7 μ A. The source was tuned on O⁷⁺. XBL 854-8859

horizontal and vertical injection lines,¹ which are performing according to design. Injection voltage is normally at 10 kV, which matches the center region requirement that dee voltage (typically 50 kV) should be 5 times the injection voltage. A drift tube buncher is used, giving a factor of 3–6 increase in external beam intensity. Beams throughout the mass and energy range have been injected and accelerated, from protons to xenon, with light heavy ion energies up to 30 MeV/nucleon. The transmission from source to total external beam is as high as 15% for low energy first harmonic beams. A typical transmission is 10%. Lower transmission beams at the top end of the 3rd harmonic mode are improved by running

higher charge states. A selection of well tuned beams spanning the first and third harmonic operating range have been used to generate predictions of settings for the injection line and cyclotron. This greatly reduces the tuning time needed for new beams. A summary of beams available is given in the 88-Inch Operations section of this report.

Future planned developments include testing of a source feed system for other solid materials, such as titanium.

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The Berkeley High-Resolution Ball*

R.M. Diamond

Criteria for a high-resolution γ -ray system are discussed. Desirable properties are high resolution, good response function, and moderate solid angle to achieve both double and triple coincidences with good statistics. The Berkeley High-Resolution Ball involved the first use of bismuth germanate (BGO) for anti-Compton shields for Ge detectors. The resulting compact shield permits rather close packing of 21 detectors around a target. In addition, a small

central BGO ball will give the total γ -ray energy and multiplicity, as well as the angular pattern of the γ rays. The 21-detector array is nearly complete, and the central ball has been designed, but not yet constructed. A schematic drawing is shown in Fig. 1, and 12 of the 21 Ge modules are shown in Fig. 2.

Footnotes and References

* Condensed from LBL-18642.

Fig. 1. Perspective view of $\sim 1/2$ the system.

XBL 819-2051

Fig. 2. Photograph of 12 Compton-suppressed Ge modules in place around a small target chamber.

CBB 846-4587

A 10" $\times$ 10" NaI Detector System

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To permit studies of both light and heavy ion radiative capture reactions at beam energies of 5–25 MeV/nucleon, a 10" $\times$ 10" NaI detector system has been acquired on long term loan from LLNL. The central crystal of this detector is surrounded by an active plastic scintillator shield and by passive ^6LiH and Pb shielding.

To accommodate this large detector system, a new beam line is being constructed in Cave 4C at the

88-Inch Cyclotron building. A 25° bending magnet has been obtained from the SuperHilac. A small scattering chamber has also been acquired from LLNL. The detector will be mounted on a cart that will be able to rotate from 20° to 150° about the chamber. In order to minimize the neutron levels at the detector position, an eight-foot deep hole is being dug into the hillside behind the cave wall. The beam line will extend from the scattering chamber to the

end of this hole, where a Faraday cup will stop the beam. The detector is scheduled to be installed in early November, and the first experiment to use this new system is planned for early December.

Footnotes and References

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A Segmented Position-Sensitive Plastic Phoswich Detector*

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In order to study reaction mechanisms at energies above 10 MeV/nucleon we needed a device able to measure energy and position of light particles and subtending a large solid angle as well. As a relatively low cost solution, we built a detector that has an active area of $20 \times 20 \text{ cm}^2$ and makes use of the "phoswich" technique to identify light particles.¹ The interesting features of the detector are the use of plastic material for both the ΔE (NE102, decay time constant $\tau=2.5 \text{ ns}$) and E (NE115, $\tau=225 \text{ ns}$) element of the phoswich. The two layers are 0.5 and 4.5 mm thick, respectively. As shown in Fig. 1, the whole detector consists of eight individual strips. Each strip is $20 \times 2.5 \text{ cm}^2$ in area and has a phototube attached at each end of the strip. Continuous position information along the strip is derived from light losses arising from multiple internal reflection of a non-ideal scintillator surface.

The phoswich strips have been tested using an 87 MeV α beam from the 88-Inch Cyclotron. The α beam was degraded in energy with aluminum foils of different thickness, providing additional energies of 79, 70, 60, 49, 35 and 14 MeV. After correction for energy straggling in the degrader foils, the energy resolution was determined to be 2.2, 2.4, 2.7, 3.1, 3.7, 5.8 and 32.8% (FWHM) for the various energies, respectively. The position resolution was found to be 0.4, 0.6, 0.8, 1.0, 1.3, 1.6 and 4.2 cm for α energies from 87 to 14 MeV. At the lowest energy the particles are stopped in the thin ΔE layer, resulting in poorer energy and position resolution due to the stronger light attenuation in this layer. Protons, deuterons and tritons are clearly separated from the α

Fig. 1. A sketch of the segmented large-area position-sensitive plastic phoswich detector.

XBL 8411-6343

particles when the 87 MeV α particles are scattered from a carbon target.

The detector was used in an experiment in which a ^{197}Au target was bombarded with an 11 MeV/nucleon ^{20}Ne . Light reaction products were recorded in coincidence with projectile-like fragments (PLF), detected in a silicon telescope positioned directly in front of the center of the phoswich detector. The most forward strip (at 6°) was operated at a count rate of 40 kHz, due mostly to elastic scattering of the ^{20}Ne beam. We observed a saturation effect of the phototubes (3/4-inch Hamamatsu R1450 equipped with E974-05 bases) at about 80 kHz. In this experiment we were able to measure α -PLF (and proton-PLF) coincidences with good statistics even for "rare" PLFs like ^{18}O and to reconstruct

primary fragment yields as well as to determine the excitation-energy partition among the primary reaction participants.

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The Response of Scintillators to Heavy Ions With $E/A < 30$ MeV

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Using the 88-Inch Cyclotron, we have tested scintillators for possible use as an E detector in a 4 π array for intermediate mass fragments formed in reactions at 20–100 MeV/nucleon. With the ECR source, trace amounts of ions up to ^{36}Ar have been obtained at 30 MeV/nucleon and up to ^{84}Kr at 9 MeV/nucleon. Scintillators of Bicron B-400 plastic, CsI(Tl), and Ce-doped glass were exposed directly to the beam. The energy and Z dependence of the light output was measured for each scintillator. These measurements have greatly extended the data available in the literature for the response of scintillators to heavy ions. This technique has also proven quite useful as a diagnostic tool for the development of new high charge state beams from the ECR source.

Table I shows a sample of beams that were obtained from the ECR source at several different charge to mass ratio values (Q/A). The cyclotron was normally tuned on one component of a mixture of several gases. Additional beams were present from impurities in the ECR source and the gas mixture. The extracted beam species was varied by sweeping the frequency of the cyclotron over a narrow range and a series of degraders was used to obtain the energy dependence of the light output for each beam species.

In general, silicon detectors cannot be made thick enough to stop fragments with energies of 20–100 MeV/nucleon. On the other hand, scintillators can be made thick enough to stop such energetic fragments. Because little is known about the

response of scintillators to heavy ions above 10 MeV/nucleon, we attempted first to define the "ideal" scintillator and then determine how common scintillator materials measured up. First, the pulse height should be linear with energy deposition. Second, for a given energy deposition, the pulse height should be independent of the Z and A of the ion species. Third, the light output from heavy fragments should be large relative to that for light particles.

Figs. 1 and 2 show the energy dependence of the light output for the plastic (Bicron B-400) and CsI(Tl) detectors. The filled circles are the present data. Most of the previously published data (with the exception of protons) is shown for comparison (opened and filled triangles). Also shown in Fig. 1 are earlier data obtained by our group for lighter ions at the 88-Inch Cyclotron and the Bevalac. The different experiments have been normalized to the present work at one overlapping point (usually O or Ne). For the plastic detector above 100 MeV the light output is linear with energy for all ions. By contrast, for the CsI scintillator the light output remains nonlinear at the energies investigated here, and together with the lower energy data of Quinton *et al.* can be fit very nicely with a quadratic expression.

The data can be used to extend the present theories of light production in scintillating material, in which the differential light output per unit energy loss ($\delta L/\delta E$) is thought to be due predominantly to

Fig. 1. Light output of a 3 inch diameter cylindrical 3 inch thick plastic detector (Bicron B400) versus the energy of various incident ion species. The filled circles are measurements from this work and the other symbols are from previous work. XBL 8510-12360

Fig. 2. Light output of a 1 inch diameter cylindrical 1 inch thick CsI detector versus the energy of various incident ion species. The filled circles are measurements from this work and triangles are from Quinton *et al.* XBL 8510-12359

the production of high energy electrons (delta rays) beyond the primary column of ionization. This condition is an effect of large values of $\delta E \delta x$ and thus should reach a maximum and then decrease at higher energies. From early data using NaI scintilla-

tors, it was concluded that this maximum delta ray production occurs at around 7 MeV/nucleon. We are in the process of applying this theory to our data in order to see if we may be nearing an energy region in which the light output may become independent of atomic number.

Of more critical importance in the selection of a scintillator for heavy ion reaction studies is the Z dependence of the light output. There are two features which are especially important. First, for heavy particles, one would like the light output to be independent of A or Z. This is not the case for any of the scintillators studied thus far. Thus, one needs information on the Z or A of the detected particle in order to fix the proper calibration curve with which to determine the energy. This can be obtained by time of flight measurements, ΔE -E measurements using a phoswich detector or a silicon-plastic telescope, or through pulse shape discrimination.

The measured Z dependence of the light output for $E/A = 30$ MeV is presented in Fig. 3. The curves were normalized for each type of scintillator to the value as $1/Z$ approached zero. One can see that plastic is the poorest as far as possible interference

Fig. 3. Relative light output per nucleon as a function of ion species mass at 30 MeV/nucleon.

XBL 8511-11510

Table I. Calibration beams obtained from the 88-Inch Cyclotron + ECR source.

Ion	Q/A	Energy (MeV)	Charge State	MeV/nucleon
$^2\text{H}2$	.500	59.6	1+	30.0
deuterons	.500	59.6	1+	30.0
alphas	.500	120.0	2+	30.0
^{10}B	.500	299.8	5+	30.0
^{12}C	.500	360.2	6+	30.0
^{14}N	.500	420.2	7+	30.0
^{16}O	.500	480.5	8+	30.0
^{20}Ne	.500	600.6	10+	30.0
^{28}Si	.500	841.2	14+	30.0
^{36}Ar	.500	1081.6	18+	30.0
^{16}O	.375	315.0	6+	19.7
^{24}Mg	.375	472.6	9+	19.7
^{32}S	.375	630.3	12+	19.7
^{40}Ar	.375	788.0	15+	19.7
^{20}Ne	.350	340.0	7+	17.0
^{40}Ar	.350	680.0	14+	17.0
^{80}Kr	.350	1,360.0	28+	17.0
^{16}O	.250	140.	4+	8.75
^{20}Ne	.250	175.	5+	8.75
^{28}Si	.250	280.	8+	8.75
^{40}Ar	.250	350.	10+	8.75
^{80}Kr	.250	700.	20+	8.75
^{84}Kr	.250	735.	21+	8.75

from light particles. On the other hand, although CsI and glass demonstrate smaller light outputs for light particles, above $A = 10$ the A dependence of their light output is no better than plastic.

The energy resolution of the scintillators was measured from the width of the observed peaks. The percentage resolution was relatively independent of Z of the incident ion, although it seemed to be somewhat smaller for fragments heavier than alpha particles. The average resolution was 1.1% for the plastic, 2.2% for the glass, and 3.4% for the CsI detector. The plastic scintillator clearly has the best energy resolution.

It is obvious from Fig. 3 that we have not yet found the perfect scintillator, if indeed one exists. However, the search goes on, spurred by the dearth of measurements in the literature, data with ECR source and the 88-Inch Cyclotron, and general interest in these results. In the next few months we plan to test BGO, BaF, and possibly other scintillators. It is hoped that this data will stimulate the theorists to develop a more quantitative theory of the scintillation process.

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MG-RAGS: A Helium Jet/Rotating Wheel System for the Detection of Short-lived Alpha and Spontaneous Fission Activities

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The old MG system at the 88 Inch Cyclotron has recently been rebuilt and is now known as MG-RAGS (Merry Go-round/Realtime Acquisition and Graphics System). Activities are transported to the MG by means of a He/KCl aerosol gas jet transport system from the actinide target system in the high level cave. In the MG, the He/KCl jet deposits the activities on thin polypropylene foils on the perimeter of a rotating wheel. These foils are stepped between eight pairs of surface barrier detectors for the measurement of alpha and spontaneous fission energies. For each of the detectors, the preamplified pulses are processed by a high gain biased amplifier for the alpha pulses and a low gain amplifier for the fission pulses. The 32 resulting signals are processed by a set of four octal ADCs in a CAMAC system. Communication to a Digital Equipment Corporation (DEC) LSI 11/73 computer is achieved by a Kinetic Systems CAMAC interface. Initial processing of the

data are performed by the computer and events are stored on a Kennedy 1600 BPI tape drive. A real-time display of the data in any pair of detectors is displayed on the computer terminal from which a set of simple commands can be used to control the whole system.

The list mode multiparameter event storage allows versatile off-line data analysis including histogramming, coincidence analysis and time correlation analysis. The two DEC RL02 20 Mb hard disk drives can be used for data analysis or program development. With a different detector system and front-end hardware, RAGS can easily be adapted for other types of data acquisition.

Some experiments have been performed with the MG-RAGS system. The main focus of this work has been to measure the mass and kinetic energy distribution from the 25 s spontaneous fission activity from ^{18}O bombardments of ^{249}Bk .

A New Chamber and Angular Distribution Table for In-Beam γ -Ray Spectroscopy

E.B. Norman

In order to measure γ -ray production cross sections of astrophysical interest, a new scattering chamber has been constructed and installed in Cave 4 at the 88-Inch Cyclotron building. The chamber is a thin walled aluminum cylinder, 6 inches in diameter and 15 inches high, its configuration allowing γ -ray detectors to be positioned close to the target position. Up to five targets can be mounted on a ladder which attaches to the upper lid of the

chamber. In order to minimize the neutron levels at the detector locations, the beam is stopped in a graphite Faraday cup located in Cave 4C. To extract total cross sections from the measured γ -ray yields, angular distribution data is required. Thus a table has been constructed and installed that allows one or two Ge detectors to view the target at a fixed distance over the angular range of 25° to 155° .

Design of a New Gas-Filled Magnetic Separator for Heavy Ion Recoils, SASSY II

S. Yashita and A. Ghiorso

The brilliant work at GSI with the velocity separator SHIP has led to the discoveries of elements 107, 108, and 109 with ever-decreasing cross sections.¹⁻³ For element 110 the production cross section is expected to be in the 1 picobarn region; this extremely low value puts its discovery out of reach using present techniques because of the enormous amount of beam time that would be required. We have analyzed this problem and have come to the conclusion that there are two approaches that could be successful within reasonable beam time constraints.

The first approach is to increase the overall efficiency of the system for guiding the fusion recoils to the detector. The second is to increase the usable bombarding beam current above the nominal 100 particle nanoamperes used at SHIP. Fortunately, both of these objectives can be attained in principle by a gas-filled magnetic separator. Such a separator has been demonstrated by our SASSY (Small Angle Separator System) to some extent;⁴⁻⁶ unfortunately, it fell short of these goals although its efficiency was comparable to that of SHIP.

The main problem with SASSY was that the long 4-meter path length of helium through which recoils had to travel resulted in substantial scatter of them outside the 30-mm high focal plane detector. In addition, the bending angle of only 22° resulted in a finite number of multiply-scattered beam particles and target-like recoils reaching the detecting silicon crystals. Our new design efforts were aimed at halving the gas path length and more than doubling the total bending angle.

We have used the BELIN⁷ computer program to accomplish these objectives within the constraints of the characteristics of magnetic components available to us at this time (Fig. 1). The system uses two dipoles separated by a horizontally-focusing singlet. To obtain the necessary vertical focusing we have added quadrupole gradients to each dipole by design-

Fig. 1. The trajectories of fusion evaporation residues in SASSY II ion optics. XBL 8512-5028

ing suitable pole tips. The equilibrated charge state condition is maintained through the magnetic system in the first two meters of path length with 1–2 torr He. As the recoil exits the second dipole it passes through a very thin window into vacuum to come to a focus about 60 cm downstream. The admittance should be ± 50 milliradians in both planes and the total bending angle is 55°. We calculate that the overall efficiency to detect element 110 recoils from the $^{209}\text{Bi} + ^{59}\text{Co}$ reaction should be better than 50% compared to the 10–20% expected at SHIP.

SASSY was able to handle as much as 100 particle nanoamperes with a fixed target because of cooling properties of the ambient helium. SASSY II has been designed to use a rotating wheel target system so that each beam pulse is spread over a much greater area. The much greater bending angle should reduce interference from unwanted particles to insignificance.

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An Improved Electronics System for SASSY II

C.H. Lee and A. Wydler

The design for a new gas-filled magnetic spectrometer for use in the heaviest element region is outlined in another paper in this Annual Report by S. Yashita and A. Ghiorso. This instrument, which separates fusion recoil products from the heavy ion beam that produces them, is expected to have a very high overall efficiency. To take full advantage of this capability for tiny cross section experiments it is necessary that the detection system be able to ob-

serve every alpha particle decay in the radioactive sequence following implantation of a recoil atom into a solid-state detector, even to registering those alpha particles that escape from the crystal before losing all of their energy. For this reason, a complete redesign of our original SASSY electronics system was undertaken and this in turn led to the incorporation of further refinements and improvements. A block diagram of the system is shown in Fig. 1.

Fig. 1. Simplified scheme of the SASSY II electronics.

XBL 8512-5027

The focal plane detector of SASSY II consists of a 50-crystal (5 wafers, 10 crystals per wafer) Si array for the time and energy measurements of alpha particle and spontaneous fission events. Each crystal is also position sensitive so that the location of each recoil implantation can be recorded. Besides the conventional electronics for amplification, master-slave ADC's, and data acquisition, the following additional equipment was added:

(1) In order to detect the minimum energy of about 1 MeV observed for a high energy alpha particle escaping normal to the face, it was necessary to increase the dynamic range of the amplifier systems. This was accomplished by dispensing with the bias amplifiers and substituting linear gates to remove the

superposition of noise from inactive channels.

(2) In order to improve gain stability and its control, we designed computer-programmable amplifier sections for each unit. A mini-computer, coupled to DAC's, was used to control the individual gains of each amplifier.

(3) In order to measure the time and energy of all decays down to the point where superposition due to pulse shape occurs (and thus times as short as ~ 200 nanoseconds), a commercial transient recorder was incorporated to observe any events that occurred during the 10-microsecond time when the master-ADC was busy. This recorder is enabled by a fast output from the pre-amplifiers whenever two successive pulses are observed within this interval.

The Di-Lepton Spectrometer Magnets: Construction and Field Mapping

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One of the most important features of the Di-Lepton Spectrometer (DLS) experimental setup, required because of the low direct electron pair cross section, lies in the large aperture magnets. Two C-dipoles (see Fig. 1) have been constructed with an open pole gap size of $111.8 \times 50.8 \times 38.1$ cm³ and a maximum nominal central field of 5 kG. Great care has been taken to reduce the fringe field by the use of field clamps, mainly to lighten the shielding of the Čerenkov and front hodoscope phototubes, but also to simplify track reconstruction. Acceptable uniformity of the field in the pole gap has been achieved with half inch thick shims around the pole tips.

The field mapping was completed in mid September. Each magnet was mapped independently at the 3 central field settings of 1.5, 3 and 5.2 kG. For each setting, the 3 rectangular components of the field were recorded in 7 planes parallel to the pole surfaces with 1225 spatial points per plane. The mapping has demonstrated that both dipoles have

Fig. 1. Front view of the magnets. XBL 8510-4411

very similar magnetic characteristics. Fig. 2 shows the central field calibration curve which starts saturating above about 5 kG. The upper field limitation is given mainly by the maximum coil power achievable. Hysteresis effects have been found negli-

gible within about 1%. Figs. 3a and 3b show the vertical field component (B_y) distribution in the mid-plane along the central particle trajectory direction (Oz axis) and along the transverse horizontal direction (Ox axis). The vertical component B_y is uniform within 3% along Ox over a distance of 95 cm. The B_y fringe field is less than 3% of the central value beyond 60 cm from the pole center along the Oz axis. The effective field length is ≈ 63 cm (along Oz). All these characteristics are in excellent agreement with the simulation calculation done at the time the magnets were designed.

We have also studied the interference of both magnets when they are close by each other, which will be the case for the high energy running of the DLS. This study has been done for all the central field settings indicated above (same setting of both magnets at a time) and for both parallel and antiparallel central fields.

The magnets are presently being moved into the Bevalac beam line 30 cave. A more complete analysis of the field mapping data is in progress.

Acknowledgements

The magnet engineering design was done by R. Reimers and the computer field simulation by S. Marks, both with the Engineering Mechanical Department. We have used a mapper system previously designed and constructed by the HISS Group. We thank the technical services and engineering division staff who set up the magnets and the mapper system.

Footnotes and References

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Fig. 2. Central field calibration curve (both dipoles have very similar characteristics). XBL 8510-4412

Fig. 3. Vertical field component (B_y) distribution in the mid plane along (a) Oz axis and (b) Ox axis. The plotted value is actually B_y over B_y at center, for both magnets at 1.5 and 3 kG and one magnet at 5.2 kG center fields. XBL 8510-4413 XBL 8510-4414

Development of Low Mass Avalanche-Counters for Beam-Trajectory Measurements

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In relativistic heavy ion collisions at the Bevalac, projectile energies range from 80 MeV/nucleon to 2100 MeV/nucleon and projectile masses from ^{12}C to ^{238}U . In order to study the projectile fragmentation (e.g., the recently observed bounce-off process) detectors must handle the same dynamic range in their response to those particles. They have to work simultaneously in an environment of high multiplicities of charged particles at beam rates up to 10^6 particles/second.

Due to the increase in the beam emittance at low energies, detectors were also needed to allow tracking of the beam particles. These requirements led to the development of one-stage avalanche detectors as beam counters and a multiplane two step avalanche detector for projectile fragment measurements. This so called Zero Degree detector was introduced in ref. 1 and is discussed in further detail in ref. 2.

To correct the scattering angle of the reaction products measured in the Zero Degree counter, two types of low mass beam counters have been designed, both with an active area of $10 \times 10 \text{ cm}^2$, a central electrode plane and a readout plane on each side (See Fig. 1). The readout plane consists of 20 μm Au-plated tungsten wires spaced 1 mm apart and located at a distance of 3 mm from the central plane. Every two wires are combined to form one pad which is read out individually via an amplifier³ and a charge sensitive CAMAC LRS 2282A ADC. The difference in the two designs is the central plane which consists of the same wires as the readout planes in the first design and is a $1.5 \mu\text{m}$ Au-coated mylar foil in the second one. The operation pressure is approximately 2 mb of n-heptane.

The test results (obtained with a ^{252}Cf fission source, 6.2 MeV α particles and in the Bevalac beam itself) revealed that the foil counter tolerated a higher electric field which resulted in much higher signals

Fig. 1. Schematic view of the beam counters (foil design) and the read-out electronics for two of the pads.
XBL 859-4099

from the wire design. Even the same voltage applied to both of the counters resulted in higher signals than from the foil design (Fig. 2), which can be understood as field inhomogeneities produced by the additional wire plane.

From these results the foil detector was considered to be better suited and has already been used in the last Plastic Ball experiment in 2100 MeV/nucleon ^{20}Ne and 150, 250 and 400 MeV/nucleon ^{197}Au beams. Since most of the secondary electrons produced in the gap between cathode and anode are collected by only one wire of the readout plane, the position resolution of this configuration is limited by the pad size of 2 mm; however, because of the distance of 4.2 m between the two beam counters the angular resolution of the beam tracks is better than $\pm 0.17 \text{ mrad}$ (rms). The efficiency of the position determination in the two coordinates is above 99% for the Au beams at an intensity of 8×10^4 particles/s $\cdot\text{cm}^2$. The simple design and operation, the thickness of only $600 \mu\text{g}/\text{cm}^2$ and the high detection efficiency even for minimum ionizing

particles at high rates make this detector a useful device for future experiments in High Energy Physics.

Footnotes and References

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Fig. 2. Pulse height of the beam counters (amplified by a factor of 200) as a function of the anode voltage obtained with fission fragments (^{252}Cf) at $p = 2.5$ mb of heptane.

XBL 859-4100

Control Program for LeCroy HV1440 High Voltage System

B.W. Kolb*

As a replacement for the LeCroy HV4032 High Voltage power supplies used for the wall photomultipliers in the Plastic Ball/Wall experiment, HV1440 systems have been acquired. Each mainframe provides up to 256 channels of computer controlled high voltage. A microprocessor controls the operation of each channel from commands received over terminal or CAMAC input. A total of 16 mainframes can be linked together and controlled with a single input device. It is planned to use this high voltage system also for the Plastic Ball (in late 1985) and later for the CERN experiment WA80 for all the calorimeters.

The interfacing CAMAC module is located in one of the CAMAC crates used for the data acquisition; I/O to the module is performed with the same hardware and software as used for the data acquisition. To handle the large amount of high voltage information an interactive control program has been

developed. This program allows one to load voltage demand values down to the mainframes, switch the high voltage on and off, read back the demand and the actual voltages, display the status of power supplies, change a group or single channels by specified amounts, change the voltage to achieve a specified change (approximate) in the gain of the photomultipliers, and document the voltages and discrepancies between demand and actual values.

All the information the program needs is stored in a database. The database contains information about the HV interface module, the connected mainframes, and all connected channels. For each channel the database holds the information about the corresponding physical quantity, i.e., the connected photomultiplier and the measured parameter, such as ADC number and name, the demand and the actual voltage. In addition, the database provides the program with information about commonly used

groups of channels. Routines written for the interactive version of the high voltage program are also called from the data acquisition program during start of a new run. This allows unattended operation of the high voltage system, because all voltages are read back and compared to the demand values in the database every time a new run is started. If there are any differences detected, the data acquisition program alerts the experimenters with a printout of the failing channels. To allow off-line correction of changed gains all measured high voltages are written to tape at the start of each run.

The high voltage program is written for the maximum configuration of 16 mainframes with 256 channels each. The mainframes and channels used are entered into the database by an interactive database program. The high voltage program and the data acquisition program extract the needed information from the database. This allows one to quickly change the connection between photomultipliers and high voltage system or to add new channels to the system.

Footnotes and References

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Study of Medium-Heavy Fragments with the Plastic Ball

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There has been considerable interest recently in the production of fragments ($A > 4$) in intermediate and high energy nucleus-nucleus collisions. The mechanism for production of these fragments is not understood and has been described in terms of various models: final state coalescence of nucleons,¹ liquid-vapor phase transitions in nuclear matter² and dynamical correlations between nucleons at breakup,³ to name just a few. All previous studies of fragment production, except one,⁴ have been single particle inclusive measurements. To gain insight into the mechanism for production of these fragments we decided to use the Plastic Ball to get full azimuthal coverage in the interesting angular range for the medium-heavy fragments while measuring all the light particles in each event. We studied the systems 200 MeV/nucleon Au + Au and Au + Fe. The Plastic Ball detector system was used with carefully lowered voltages in the Outer Wall (2 to 10 deg.) and Mall (10 to 30 deg.) to allow detection of the medium-heavy fragments without losing the ability to detect protons. These lab angles encompass most of the fragment emission from the projectile spectator and fireball regions for the systems studied.

Furthermore, the forward motion of these systems minimizes the low energy cutoffs of the detectors.

3.4 million events were collected for Au + Fe and 2.2 million events for Au + Au during two week-ends of successful running at 200 MeV/nucleon at the Bevalac. An example of the online particle identification in the Mall is shown in Fig. 1. Nuclear charge identification from hydrogen to oxygen is discernible. In addition, with the display gain increased ^{1,2,3}H and ^{3,4,6}He separation was achieved. In the Outer Wall, elements up through carbon were detected. A Mall module was calibrated in a separate experiment using a 320 MeV/nucleon carbon beam which was degraded and fragmented. In this experiment the energies of the fragments were measured by time of flight. The calibrations and processing have now been completed and the data analysis is in progress. The multiplicity and correlations of the medium-heavy fragments will be determined, as well as the flow of these fragments relative to the reaction plane determined by all the other fragments. All of the analyses will be done as a function of the total charged particle multiplicity (impact parameter)

determined by the Plastic Ball.

Footnotes and References

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Fig. 1. A particle identification spectrum for all the Mall modules added together. XBL 8510-4377.

Emulsion Chambers for High Energy Fragmentation Studies

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Bevalac Experiment 744H was performed in order to irradiate a series of prototype designs of emulsion chambers to relativistic ^{56}Fe and ^{16}O beams. The chambers will be used to carry out CERN Experiment EMU01 on the "Study of Particle Production and Nuclear Fragmentation in Collision of ^{16}O -Beams with Emulsion Nuclei at 50–225 GeV/nucleon," scheduled for 1986–7. This experiment is an international collaboration of nine laboratories, with Dr. Ingvar Otterlund, Lund University, Spokesman.

The objectives of the experiment are to: 1) establish the design of the emulsion chambers for the CERN experiment, 2) determine the resolution in measurements of the pseudo-rapidity of produced particles with the chambers, the efficiency for detection of $Z=1$ relativistic particles, and the pattern recognition capability of our event reconstruction procedure.

Fig. 1 is an expanded view of the prototype detectors. The design optimizes our ability to characterize interactions with high multiplicities and to study in detail the multiplicity distributions as a function of pseudo-rapidity. With these chambers very accurate angular measurements will permit the determination for each event, not only the whole pseudo-rapidity distribution, but also of possible fluctuations in this distribution and correlations between one or more tracks. As illustrated in Fig. 1, the chamber is configured with (five) 75 μm -thick electron-sensitive Fuji emulsion layers on both surfaces of metacrylate bases, an active target layer of 800 μm -thick Ilford emulsion supported on glass and (three) 1/2 in-thick honeycomb spacers. The chambers have a $10 \times 10\text{cm}^2$ area whose normal is positioned along the beam direction during exposure. Schematically shown in Fig. 1 is an incident beam nucleus entering the chamber (from the left). The track-image at the emulsion-plastic interface (IF)

numbers 1 through 4 establish the direction of the incident nucleus. The nucleus is observed to interact in the target emulsion T, with the secondary fragments being observed and measured at the emulsion-glass IF 6 and, subsequently, at IFs 7 through 12.

We have completed measurements on a sample of 1.8 GeV/nucleon ^{56}Fe interactions having high multiplicities in the forward projectile fragmentation cone. Using our ICAMS microscope system, we used the following procedure for event reconstruction.

- 1) All emulsion plates are mounted and positioned in frames, physically aligned to approximately $\pm 200\text{ }\mu\text{m}$ when placed on the measuring stage.
- 2) The x-y coordinates of all tracks are measured to $\pm 1\text{ }\mu\text{m}$ at each interface, as are the coordinates of selected background beam tracks that are used to accurately align the emulsion layers in the chamber.
- 3) Given the xyz coordinates of the event in the target emulsion and the coordinates of a track at any interface, a prediction of the coordinates of the track at the next interface is made.
- 4) The microscope is driven to the predicted point, the track is visually located and a measurement of the xy coordinate is made (z coordinates is the position of the emulsion-plastic interface).

Fig. 2 shows the reconstruction of a typical Fe interaction, giving rise to about 30 projectile and target fragments in a 20° forward cone. Displayed is the x versus z (beam direction) coordinates, with the points indicating the position of each track at an emulsion-plastic interface. The trajectories of the secondary particles radiate from the sites of the interaction in the target emulsion.

We give in Table I the rms deviations between the predicted and measured coordinates of all secondary tracks at interfaces 7 (the first emulsion-plastic interface below the target emulsion) through 12, based on 76 tracks.

The largest uncertainties in our predictions occur at IFs 7, 9, 11, i.e., extrapolations of the tracks

through the 1.3 mm glass base and 1/2 in-thick honeycomb, respectively. The predictions through the 0.75 mm-thick plastic bases, IFs 10, 11, and 12, are $\approx \pm 5\text{ }\mu\text{m}$. Given the precision of the predicted coordinates and the vector direction of the track segment observed in the emulsion layer, track following was unambiguous and 90–95% efficient (which includes loss due to interactions).

Fig. 1. Schematic diagram of emulsion chamber. P: 75 μm -thick emulsions on 0.75 mm-thick plastic base; HC: 1.27 cm-thick honeycomb spacer; S: 25 μm -thick glassine paper; T: 800 μm -thick emulsion (target) on 1.3 mm glass. Chamber is $10 \times 10\text{ cm}^2$ in area. The distance between interfaces (IF) 1 and 12 is 4.476 cm. XBL 8510-4342

Fig. 2. Coordinates of the trajectories of tracks of ^{56}Fe interaction, projected on x-z plane. Points are measured coordinates at each interface. IFs 1–4 establish the beam vector. IFs 7–8 establish the vectors of secondaries, as illustrated in Fig. 1.

XBL 8510-4340

Table II gives the results of a least-squares linear fit to the trajectories of four projectile fragments ($Z=1$ and 2) of the event shown in Fig. 1.

The results of these measurements show that the spatial coordinates of particle tracks in the prototype chambers can be determined to within $\pm 1-2 \mu\text{m}$, with their vector directions determined to ± 0.1 mrad. These errors are compatible with those expected from our $\pm 1 \mu\text{m}$ digitization of the x-y coor-

dinates and multiple scattering of beam-velocity fragments.

These observations give excellent evidence that the objectives of CERN Exp. EMU01 can be met, and the emulsion chamber configuration we have investigated can yield the necessary spatial resolution to detect particle densities at the highest predicted particle production in ^{16}O -emulsion collisions at 225 GeV/nucleon.

Table I
RMS Deviations Between Predicted and Measured Coordinates,
Interfaces 7-12.

Interface (IF)	7	8	9	10	11	12
Meas.-Prod. (μm)	22 ± 12	7 ± 4	17 ± 5	5 ± 3	12 ± 2	3 ± 1
(rms)						

Table II
Results of Least-Squares Fit to Trajectories of Secondary
Tracks, Coordinates at IFs 7-12

Track	1	2	3	4
Space angle θ (mrad)	$24.13 \pm 0.07_2$	$27.36 \pm 0.08_8$	$24.14 \pm 0.10_2$	$10.99 \pm 0.10_1$
(rel. to normal)				
$\sigma(\theta)(\text{ave})$	$\pm 0.091 \pm 0.014$ mrad			
$\sigma(x,y)(\text{ave})$	$\pm 1.4 \pm 0.5 \mu\text{m}$			

Status Report on the Di-Lepton Spectrometer (DLS) Design and Construction

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The DLS Collaboration research program involves the study of direct electron pair production at Bevalac energies in p-nucleus and nucleus-nucleus collisions. The reader is referred to the 1983-84 Nuclear Science Division Annual Report¹ for more information on the Physics objectives and a general presentation of the experimental setup.

Fig. 1 shows a layout of the system as it will be installed in the Bevalac beam line 30 cave. The scattering chamber has a conical shape in order to provide a minimum amount of material along the particle trajectories into the spectrometer together with the use of a multiplicity array detector positioned around the target. The multiplicity array, not

shown on the layout, will have 64 scintillator segments covering an angular range of 10 to 60° in theta and 250° in phi. A simulation using intranuclear cascade events² has shown that we should get reasonably good information on the multiplicity for nuclear beams up to ⁴⁰Ca or ⁵⁶Fe.

The present design of the 1 atmosphere gas Cerenkov counters includes 3 mirror segments in the front viewed by 3 phototube-Winston cone assemblies and 10 mirror segments in 2 layers in the rear, each mirror being viewed by 2 phototube-Winston cone assemblies. This arrangement of the rear counters provides a convenient way of optimizing the light collection and the opportunity of getting additional information on the charge sign of the particles: 2 different sign electrons will enter the field of a given mirror at symmetrical angles relative to a straight line from the target and mainly emit their Cerenkov photons towards either one of the 2 phototubes.

Scintillator hodoscopes on each arm (front and rear of magnets) will provide accurate time of flight information and offer the possibility of using the system in a single arm trigger mode. There will be 1 phototube per segment in the front and 2 phototubes per segment in the rear.

We are presently constructing 6 drift chamber stacks, 3 on each arm (1 in the front and 2 in the rear), each stack with 6 sense planes XX'UVYY'. The U and V wires will be at $\pm 30^\circ$ with respect to the vertical. A third stack in the rear on each arm might be added later.

The front stacks are made with G10 frames (6 mm in thickness). They have uniform cathode potential so that cathode planes can be common to 2 contiguous sense planes. There are 7 cathode planes per stack, 4 with the wire direction along X and 3 with the wire direction along Y. Several prototype planes have been made and studied. We have found that a drift length of 1 cm and a cathode wire spacing of 1 mm is adequate. The sense wires are Au plated W, 25 μ in diameter, and the other wires Cu/Be, 75 μ in diameter. The drift chambers are filled with a gas mixture Argon-Ethane 50%-50%, the total average thickness in radiation length (not in-

Fig. 1. Layout of the DLS.

XBL 8510-4415

cluding the mylar windows) being $4 \cdot 10^{-4}$ per sense plane.

In order to reduce the construction cost of the rear stacks, we are making the frame of Pultrusion, borrowing the molding technique from the MPS II drift chambers at BNL.³ The cathode planes are of the field shaping type with a wire spacing of 3 mm, the drift length being 18 mm. Each cathode plane is neighbored by a shield plane of again 3 mm wire spacing, thus bringing to 25 the total number of wire planes per stack (6 sense, 12 cathode and 7 shield planes). A prototype stack of the largest dimensions (active area of $200 \times 67 \text{ cm}^2$), 3 sense planes XX'X and the corresponding cathode and shield planes has been constructed using the same wires as for the front chambers. The prototype has been studied over the summer and is still under investigation. We were able to fix some minor design and construction faults. Using a cosmic ray trigger, with LRS 2735A edge cards and LRS 1879 FASTBUS TDCs⁴ we have so far obtained a resolution of 350 μ (see Fig. 2) with a reconstruction efficiency over 93%. Fig. 3 shows the electrostatic equipotential distribution for the optimized voltages. It appears that the initial gradients on the cell edge wires were too high and might trigger field emission and possible whisker

Fig. 2. Error distribution in the center plane of the prototype stack ($\Delta x = x_2 - \frac{x_1 + x_3}{2}$). The RMS value is 409μ corresponding to a spatial resolution in each plane of 335μ . XBL 8510-4416

Fig. 3. Electrostatic equipotential distribution for optimized voltages over two contiguous cells of the rear drift chambers. XBL 8510-4418

growth on these wires. We have therefore decided to increase the diameter of the wires at the cell edge from 75μ to 150μ , at the expense of increasing the

amount of material (the thickness in radiation length went from 5×10^{-4} to 7×10^{-4} per sense plane).

The CERN GEANT 3 library has been implemented on our VAX 11/750 computer and a first version of the DLS simulation program was completed by late January. Since that time, the program has been extensively used in the acceptance and expected rate calculations, and in the design of the detectors. More recently, the tracking of the Čerenkov photons has been introduced in the code. At this stage where spherical shapes are not yet available in GEANT, the spherical mirrors have been simulated by plane facets (up to 81 plane facets per mirror segment). Fig. 4 shows an electron track with about 30 Čerenkov photons in the front counter. Besides its interest during the design phase, the code will be used in the data analysis for generating the DLS acceptance and the momentum reconstruction algorithm.

The magnet construction and field mapping are described in another article of the present Annual Report and the FASTBUS based data acquisition system is presented elsewhere.⁴ The first test runs of the DLS with nuclear beams (probably ^{20}Ne at the beginning) are scheduled in May of 1986.

Acknowledgements

The rear drift chamber final design has been aided by J. Va'vra, SLAC EFD Group, who provided in particular the field distribution study (Fig. 3) and suggested the increase to the wire size at the cell edges. The CERN GEANT 3 library has been implemented in the DLS simulation code with the collaboration of R. Brun, CERN Data Handling Division.

Footnotes and References

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Fig. 4. A GEANT simulation of an electron track with Čerenkov photons in the front Čerenkov counter.
XBL 8510-4417

A Multiple Sampling Ionization Chamber (MUSIC) for Measuring the Charge of Relativistic Heavy Ions

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MUSIC (MULTiple Sampling Ionization Chamber) is a large-area ($1\text{m} \times 2\text{m}$) detector used to determine the charge and trajectory of relativistic heavy ions at HISS (Heavy Ion Spectrometer System). Current experiments in progress with MUSIC include investigations of charge changing cross sections and of transverse momentum distributions.

MUSIC consists of a large cylindrical gas-tight vessel (3m in diameter $\times$ 2m long) containing a field cage ($1\text{m} \times 2\text{m} \times 1.6\text{m}$ deep) and two $1\text{m} \times 1.44\text{m}$ sections of 64 anodes each (60 2-cm anodes and 4 6-cm anodes). This allows the energy loss per distance traveled to be measured up to 64 times along the path of a charged particle, enabling the reconstruction of the energy loss distribution. The mean energy loss per unit distance is proportional to $(Z/\beta)^2$. If the velocity spread of the particles is small, the β dependence becomes negligible (the velocity can be measured separately if need be).

The electronics used to record the energy loss are those developed for the TPC (Time Projection Chamber) operating at SLAC. The electron cloud from the ionizing particle is drifted down through a grounded Frisch grid by the uniform electric field in the field cage. The electrons are collected on the anode wires which are coupled to individual charge sensitive preamps. The signal from each preamp is fed into a shaping amplifier, then into a stack of CCDs (Charge Coupled Devices), into an ADC, then into a threshold comparator, and finally into a memory buffer from which the data is read by a PDP 11-45 onto tape. This provides an amplitude versus time profile of all signals over threshold for each wire. Fig. 1. shows the profile for a La ion track in the first 15 2-cm anodes of MUSIC. From the drift time at each wire we can calculate the vertical position and slope of the particle track. Spatial resolutions of less than 1 mm are possible, though two particles must be vertically separated by approx-

Fig. 1. Lanthanum track through MUSIC.

XBL 8510-4331

imately 2 cm to be identified.

We have found that the most delicate aspect of the detector is the gas system. We use P-10 (93% Ar + 7% CH₄) as our counter gas. For MUSIC to properly function, the proportion of electro-negative impurities must be no greater than about 1 ppm. To achieve these purities we put steel endcaps over the thin mylar-copper windows, evacuate the entire chamber then refill it at least twice. The endcaps are then taken off and pure Ar is pumped through the windows. Each window consists of two mylar-copper sheets with a space in between for gas circulation.

The mean rate of energy loss of a charged particle in a medium is given by the Bethe-Bloch equation which has a minimum at relativistic energies ($E=3\text{-}mc^2$). The energy loss distribution we find in MUSIC is a modified Vavilov distribution. If only primary ionization is considered, ionization of a thin medium follows a Poisson distribution. When secondary ionization due to high-energy delta rays is accounted for, the ionization is described by the Landau distribution. If in addition we realize that there exists a maximum value for the energy the particle can transfer to a single electron, the Landau distribu-

tion becomes the Vavilov distribution. However, not all the energy lost by the charged particle is deposited in the medium if it is thin enough. Some of the delta rays will escape from the medium, taking energy with them. Assuming that delta rays with a range in Ar greater than the width of an anode deposit some constant energy (E_{max}) in that cell yields the ionization ($\propto$ energy deposited) distribution observed in MUSIC. G.D. Badhwar has done just such a calculation and obtained results that are in good agreement with our own observations.¹

Since the low energy side of the Vavilov distribution is much sharper than the high energy tail, one might expect better resolution by sampling the energy loss of an ion and reconstructing this sharp edge. However, the loss of high energy delta rays causes the distribution to become narrower and more gaussian, increasing the resolution and decreasing the need for multiple sampling. We find that without accounting for the asymmetry of the distribution (i.e., by simply averaging the N energy losses) we obtained charge resolution of 0.25e FWHM for 727 MeV/nucleon Ar and 0.30e FWHM for 1.08 GeV/nucleon La.^{2,3,4} Fig. 2. shows the energy loss measured for $Z=55,56,57$ and the clear separation of charges. Fig. 3. shows the charge spectrum measured in the 2-cm anodes for fragmentation of 1.08-GeV/nucleon La on a C target.

MUSIC's charge resolution and dynamic range are inexorably linked. By placing coupling boxes between the anodes and the preamps, each half of MUSIC can be operated with any anode configuration from 60-2cm anodes + 4-6cm anodes up to one 144cm anode. In addition, a patch panel in series with the analog signal from the preamps allows attenuation of the signal into the shaping amplifiers, further increasing the possible dynamic range for a given configuration. Our tests indicate that MUSIC can cover a range of fifty charges with a resolution of about 0.5e FWHM or eighty charges with a resolution ranging from 0.4e FWHM for the highest charges down to about 0.7e FWHM for the lowest charges ($Z_{\text{min}} \approx 6$). Better charge resolution can be obtained for any smaller range of charge for $6 \leq Z \leq 100$.

Fig. 2. Energy Loss for Charges $Z=55, 56, 57$.

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Fig. 3. Charges $Z=25$ through $Z=57$.

XBL 8510-4333

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Drift Chamber for HISS

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Last year we tested the response of a prototype drift chamber to various heavy ion beams from the Bevatron. The analysis¹ included the development of a real track finding program. From the study we found that it was necessary to add more planes with vertical sense wires to increase the track finding efficiency and the Phase 2 drift chamber for the HISS detector system is now being built with these improvements. The new chamber has a larger geometrical acceptance (2 m horizontal and 1.5 m vertical), more redundancy (15 sense planes separated by 10

cm), and larger dynamic range in particle charges compared with its predecessor.

This summer the prototype chamber was used in experiment E772H to measure various projectile fragments from ^{40}Ar beams at 1.65 GeV/nucleon together with the new Čerenkov hodoscope and the target multiplicity detector. The combined detector system gave perfect particle identification at 1.6 GeV/nucleon between $Z=4$ and $Z=16$. The response of the prototype chamber to various fragments was studied under the actual experimental conditions and

it was found that an overall position resolution of $\approx 300 \mu$ can be achieved for all the fragments. The overall efficiency of the prototype chamber including the track finding was 50% at $Z=5$ and essentially 100% for $Z \geq 8$. We expect that the full chamber efficiency will extend to $Z=57$ with the same position resolution.

The Velocity Measuring Detector

D.L. Olson

We have constructed a charge and velocity measuring hodoscope using total-internal-reflection Čerenkov counters of a type mentioned by Jelly¹ in 1958. This velocity-measuring-detector (VMD) was used as an integral part of the isotope identification procedure in the first run of HISS experiment E772H. Our preliminary analysis yields a charge resolution of $\Delta F_{FWHM} = 0.5e$ and a mass resolution of $\Delta M_{FWHM} = 0.5u$.

A schematic diagram of the device is given in Fig. 1. In its present configuration it is composed of 36 glass² and 36 fused silica³ Čerenkov counters and has a frontal area of $0.25m \times 1.0m$. The individual Čerenkov radiators are 30cm long, 0.5cm thick and taper from 4cm to 3cm wide. An Amperex XP2202 photomultiplier tube is attached end-on to the 4cm wide surface. The radiators are arranged so that the edges overlap in order to provide full coverage over a range of incident angles.

Operating Principle

A complete description of these counters are given in ref. 4 and the essential characteristics are summarized here. Čerenkov light is produced at an angle $\theta_c = \cos^{-1}(1/\beta n)$ relative to the direction of a particle with velocity β passing through a material of index of refraction n . The number of photons produced per unit wavelength interval per unit thickness of radiating material is $dI/d\lambda \approx Z^2 \sin^2 \theta_c / \lambda^2$ where Z is the charge of the particle and λ is the wavelength of the light. When the particle is traveling through a medium for which all the surfaces are either perpendicular or parallel to the direction of the particle the

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Fig. 1. Diagram of the velocity-measuring-detector (VMD). The radiators overlap so as to provide full coverage for $0.25m$ by $1.0m$. XBL 8511-4559

Čerenkov light is trapped within the medium if $\theta_c > \sin^{-1} 1/n = \phi_{crit}$, the critical angle for total internal reflection. Since real materials are dispersive

($n=n(\lambda)$) the light is produced over a range of angles and this threshold is not a step function but has some width in β . The result is that this type of counter is sensitive to velocity in the threshold region of $\theta_c \sim \phi_{crit}$.

The theoretical response of this type of detector is shown in Fig. 2. For particle velocities near threshold these counters are extremely sensitive to velocity while for higher velocities the response is very insensitive to velocity and depends only upon the charge of the particle. These two regions correspond to the velocity measuring mode (near threshold) or the charge measuring mode (well above threshold).

As can be seen from Fig. 2 the response is very nearly linear in velocity over a range in the threshold region. Therefore, we can approximate the velocity dependence as $Q = aZ^2(\beta - \beta_0)$, where Q represents the signal from the fused silica radiators. By measuring Z with the glass radiators we then get $\beta = Q/aZ^2 + \beta_0$ where a and β_0 are calibration constants. If we combine this measure of velocity with a rigidity measurement we can derive the mass of the particle. Since rigidity is momentum/charge, $R = P/Z = \gamma\beta Au/Z$, so we then have $A = ZR/\gamma\beta u$.

Experimental Results

The experimental results presented here are from E772H which is a 1.65 GeV/nucleon ^{40}Ar projectile fragmentation experiment. The setup for E772H has the target about 3m upstream of the HISS magnet and the 30cm by 40cm prototype drift chamber in front of the VMD which was about 8m from the target on the downstream side of the HISS magnet. Wire chambers upstream and the drift chamber downstream provided the tracking measurements needed for the rigidity analysis. The glass and fused silica radiators in the VMD provided the charge and velocity measurements.

The preliminary results of the projectile fragment mass determination are shown in Figs. 3a,b and c which includes data from the whole surface of many radiators. Fig. 3a shows a scatter plot of the charge Z of the fragments versus the mass number A . Figures 3b & c show histograms of the charge and mass. The resolution at this point in the analysis is

Fig. 2. Calculated response curves for three different radiator materials, (a) fused silica, (b) lucite, and (c) UBK7. The data points are from prototype tests of a fused silica radiator. XBL 8410-4295

Fig. 3. Preliminary results from E772H for isotope identification. (a) is a scatter plot of Z vs. A in which the individual isotope peaks are clearly visible. (b) is a histogram of charge showing a resolution of $\Delta Z_{FWHM} = 0.5e$ independent of Z . (c) is a histogram of A showing a resolution of $\Delta M_{FWHM} = 0.5u$ independent of A . XBL 8511-4560

$\Delta Z_{FWHM} = 0.5e$ and $\Delta M_{FWHM} = 0.5u$ for ^{40}Ar projectile fragments.

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Fastbus Based Data Acquisition System for the Di-Lepton Spectrometer at the Bevalac*

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A new experiment,¹ which is called the Di-Lepton Spectrometer (DLS), is being constructed to measure the threshold dependence of electron-positron pairs. In this experiment it will be necessary to digitize the usual information and to store it on magnetic tape. Time to digital converters (TDCs) and analog to digital converters (ADCs) are used to measure respectively the time and amplitude information for the Čerenkov and the hodoscope counters. Drift chamber information is recorded with lower resolution TDCs. In order to modernize the electronics for accelerator experiments, a new standard, FASTBUS, has recently been developed.² Commercial modules are now available so that it is possible to use this new standard easily. Because of the cost, new features in these modules, and the high packing density, we have decided to use FASTBUS modules which are commercially available. All electronics in this experiment have been fabricated by commercial sources.

Fig. 1 shows the block diagram for the data acquisition system. All FASTBUS data are collected in the FASTBUS crate by a LeCroy 1821 segment manager. The segment manager has been programmed to read all the drift chamber hits and ADC channels above pedestal. FASTBUS data are transferred to CAMAC through a LeCroy 2891 CAMAC interface. A MBD built by the BiRa Corporation is used to transfer both the CAMAC and FASTBUS data to a VAX 11/750.

Fig. 1. Block layout of the data acquisition system.

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We have selected the LeCroy 1879 TDC to digitize the time from the drift chambers. At its highest sensitivity of one nanosecond per channel and with its range of one microsecond, the TDC is well matched to the resolution and drift length for our chambers. Measurements of the resolution of the TDCs have shown an intrinsic resolution of 0.7 to 1.2 nanoseconds per channel. This value is sufficient to achieve the expected resolution of about 300 microns for the drift chambers.

To measure the pulse height of the Čerenkov and hodoscope counters, we have selected the

LeCroy 1882 ADC FASTBUS system. These ADCs have sufficient resolution and linearity so that we can separate protons from minimum ionizing particles.

The process of obtaining data and writing that information to magnetic tape requires programming three computers. The segment manager assembles the FASTBUS data. The MBD collects the CAMAC data and then sends it through the UNIBUS to the VAX 11/750. The VAX formats the data so that it can be written on magnetic tape and sends it to a disk file so that online analysis can be done on it. The disk file will be read both by the VAX 11/750 and another VAX 11/780 so that online data checking can be made.

The segment manager has been programmed using an micro-assembler to read out only those modules which have data in that event. First a broadcast is sent over the backplane to lock in all the ADCs. The channels are read and then piped to the 1821 memory. In this process, a pedestal subtraction is made. Only those modules which exceed a specified threshold are written to the memory. Next, using TPOLL logic, only those TDCs which contain hits are latched to the 1821. Data are read and then stored in the 1821 memory. A major advantage of the way that this code is written is that no change has to be made to either increase or decrease the number of TDCs or ADCs that are read each event.

After all data is transferred to the 1821, a Microprogrammed Branch Driver (MBD) transfers the data via CAMAC to the memory of a VAX 11/750. The coding of the MBD is very simple as it only takes about thirty 16 bit words to program the reading of the whole FASTBUS crate. It takes about 8 microseconds per FASTBUS 32-bit word to move the data to the VAX after the addresses have been digitized. While this time is slow compared to maximum speed of FASTBUS, it is fast enough compared to low trigger rate for this experiment. Using this system, we can collect about 100 events per second.

At present the complete data acquisition system has been tested using a few counters and a prototype drift chamber using cosmic rays. These tests

have been made with almost a whole FASTBUS crate full of electronics -- 16 TDCs and 1 ADC. Over a period of three months we have had no failures with the FASTBUS system. This data acquisition system has worked so reliably that many members of our collaboration have used it without needing detailed knowledge of FASTBUS. Fig. 2 shows a typical pulse height distribution for a scintillator counter from a FASTBUS ADC. That figure clearly shows the pedestal of the ADC and the signal from the light deposited in the scintillator. Similarly, Fig. 3 shows the time spectrum for one wire from a cell in our drift chambers. At earliest time is the signals from hits close to the anode wire; at later time are the hits which occur farther away from the wire. The width of this spectrum is consistent with a drift region of 1 cm and a drift velocity of 50 microns per nanosecond.

Fig. 2. Pulse height spectrum for a scintillator. The data was taken with a LeCroy 1882 FASTBUS ADC. XBL 8510-4322

Fig. 3. Histogram of the time for drift chamber hits for one wire. This data was taken using a LeCroy 1879 FASTBUS TDC. XBL 8510-4323

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CCD Supervision System for CERN NA-35 Experiment

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The NA-35 supervision system will facilitate on-line monitoring of the streamer chamber performance and event topology by employing two high resolution, high sensitivity charge-coupled device (CCD) cameras linked directly to a high speed image processing system. One camera will view the entire chamber volume in order to monitor track multiplicity, event topology and overall chamber performance. The second camera will have higher magnification, imaging only the downstream part of the streamer chamber, and will assist the first camera in the higher density projectile fragmentation region while also monitoring track profiles to insure quality chamber response.

Details of the supervisory functions planned for the system will now be described. This system must supply high quality pictures, have a simple and flexible operator interface, and provide quantitative information for interactive queries and standard background monitoring. Elementary measures of track brightness and event topology are necessary for controlling the high voltage system and the trigger. Further track information is useful for correlation with the calorimeters in online data analysis. While it is not intended that many whole CCD pictures will be stored for offline analysis, an archive of standard parameters extracted from each picture will be

recorded.

Development of the supervision system will proceed in phases, from the highest priority and least difficult to the lower priority, more difficult tasks. Since our approach is to use standard modular hardware, and control the supervision system with software developed in-house, evolution and customization of the system will be possible. Below is a list of these functions in order of importance to the supervision system (and development). Some of these functions are simply commercial hardware facilities (e.g., the graphics display). Items 1-9 are relatively straightforward while the remainder requires significant development. It is difficult at this time to predict the feasibility and completion date for these last functions. The entire list follows:

1. A high resolution screen display (preferably at least the same Pixel count as the cameras);
2. Display in pseudo-color to present the pixel intensity information usefully, and provide graphic overlays;
3. User-controlled zoom and pan of the display over the picture;
4. A cursor-control system to define points, lines, and windows; get screen coordinates, pixel in-

tensities, and intensity profiles across sections of the image;

5. A quantitative monitor of the chamber laser track intensity;
6. A high resolution hardcopy of a display;
7. Let the user switch easily between camera views, and display multiple views simultaneously in windows on the screen;
8. Histogram pixel intensity values over areas of the picture, and let the user define intensity level cuts;
9. Follow single tracks from a starting cursor position, and put graphic overlays on tracks;
10. Derive an approximate multiplicity for an event;
11. Find a projected pseudo-rapidity distribution for an event;
12. Determine whether the primary vertex coincides with the target;
13. Histogram intensity per unit length for a subset of tracks;
14. Find track exit points on the chamber walls, given prior knowledge of the wall locations;
15. Attempt one-view reconstruction of single tracks to give single-particle momentum spectra.

The imaging system will consist of two high resolution Photometrics cameras with (1024×1024 pixels) Texas Instruments CCDs. One camera will have a demagnification of 130 and view the entire 2 meter streamer chamber while the second with a demagnification of 30–40 will focus on the forward projectile fragmentation cone. The TI CCDs have a quantum efficiency of 40–50%, resulting in a sensitivity greater than film. The use of image intensifiers will be an option for low chamber voltage, low light output running. The CCD pictures will be digitized to 8 bits and transferred in parallel to the on-line image processing system.

The image processing system will be based on a MicroVAX II computer, with an attached 10 MIPS 16 bit integer coprocessor, the Mercury Computer Systems 3216. The MicroVAX II will be a VAXStation II package, including a full 32 bit VLSI CPU with floating point accelerator, 11 Mbytes memory, a 71 Mbyte Winchester disk, 95 Mbyte streaming cartridge tape, 800 Kbyte floppy disk, a 1024×864 monochrome console display, and a large BA123 box with 12 Q-bus slots. The Mercury system includes parallel control and arithmetic processors, a 10 MHz, 32 bit internal bus, 2 Mbytes memory, two 16 bit high speed IO ports, and a DMA Q-bus interface. An image processing software library and a C programming language compiler are available for the Mercury. The CCD cameras will be interfaced to the system through the Mercury IO ports, so the picture input and initial processing can proceed at high speed in parallel with the host MicroVAX. A high resolution (1024×1024) 8 bit pseudocolor graphics system will be attached by fast DMA interface to the Q-bus for display. This will provide hardware graphic overlays, cursor control, zoom and pan for flexible interaction with the user. There will also be a high resolution color hardcopy device.

The data stream will consist of the following: an event will be recorded by the two CCD cameras, and then the images read into the Mercury in an interleaved fashion. The Mercury will then perform filtering operations on the images in its memory to reduce background and clarify the pictures. The data will then be copied into the MicroVAX and to the display. The user will be able to examine the event interactively on the screen, while other processes in the MicroVAX analyze the image for track multiplicity, projected pseudo-rapidity, track profiles, etc. Standard parameters such as laser track intensity and primary vertex position will be monitored and logged automatically. The system can cycle automatically, or be cycled by the user.

Computerized Measuring and Scanning

*K.L. Wolf and J.P. Sullivan**

Stage 1 of this project, which will be completed by November 1986, configures an ALICE(POLY) type of system as we had done at Argonne National Lab over three years ago, but based on more modern hardware and software. The software for track profiling and vectoring is currently being written on a VAX 11/780, which will be the host computer with a CCD line reader. Pixel resolution is software controlled up to 1700×2800 , with a zoom lens feature which allows higher resolution in selected areas as needed in reiterative reconstruction. Full three view reconstruction will be made with track coordinates, ionization density measurements, and matching criteria extracted with computer methods.

The major thrust of measurements performed previously was to develop methods for fully computerized measurement, reconstruction, and matching for low multiplicity ($M=25$) events. Scanning rates were increased by factors of 10–100 compared to manual scanning. Ionization density measurements for particle identification are much improved. Computer matching of corresponding tracks in three views was performed by spatial and track feature considerations. Table I gives the rates attained for low multiplicity ($M=25$) events and our estimates for $M=50$.

Reliable estimates for higher multiplicities cannot be made at this time. Stage 2 of this project will add a high resolution graphics system for interactive capability, if necessary at high multiplicity, and a faster CCD line reader if it is needed.

Stage 2 VME-Based System

We have begun ordering components for a VME-based system after three months of evaluation and design study. The system will allow three 5 Mbyte pictures to be digitized and stored in memory simultaneously for analysis. Measuring and matching times will be reduced considerably over the stage 1 system. A $1000 \times 2000 \times 8$ bit color graphics system will be used for development and for a manual assist mode in regions of extremely high track density. A 16.6 MHz 68020 cpu with 0.5 Mbyte of on-board 100ns dynamic RAM program memory will be used to control the system. A pipelined processor will be added for faster floating point operations in the TVGP and vertex reconstruction programs

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Table I - time for each stage of processing 35 mm film from the LBL streamer chamber for charged particle multiplicity $m = 25$ events, and estimates for $m = 50$ events. The second line for $m = 50$ includes rescanning a section of the frame at higher resolution.

M	Digitization (sec)	Measure (sec)	Match (sec)	Reconstruct (sec)	Total (sec)	F
25	90	30	2.5	32.5	155	98%
50	90	70	50	65	275	80%
50	180	120	75	90	465	96%

Report on TOF at 900 MeV/nucleon*

H.J. Crawford,[†] P.J. Lindstrom, I. Flores,[†] and G. Krebs

This note describes our measurements of the time-of-flight (TOF) of 900 MeV/nucleon Au ions at the Bevalac¹ as part of an investigation of relativistic and higher order (Z^3) terms in the range-energy relation for heavy ions traversing matter.² The goal of this measurement was to provide beam energies to an accuracy of better than 0.5% at 900 MeV/nucleon. Using two small scintillators and a flight path of 18.5 m we achieved time resolutions of better than 40ps per detector and an overall energy resolution of better than 0.4% (3 MeV/nucleon). This resolution can be improved using faster tubes and faster scintillators. We discuss in an appendix the variation of energies within a Bevalac "spill".

The setup of the beam line and scintillators is shown in Fig. 1. In the "T0" position, scintillator S2 was placed 5cm behind S1 in the same vacuum box. Each scintillator was in a cylindrical, light tight container, having walls in the beam direction of 0.001" Al foil. In the "T1" position, S2 was moved out of the vacuum to a remote controlled cart in the cave area. Note that the same scintillator, cables and electronics were used in the T0 and T1 positions. The T1 flight path was vacuum from S1 to within 10 cm of S2, the vacuum being sealed with a 0.004" thick Al window.

We determined the total flight time and hence the particle velocities using our 50 ps/channel normal TDC. The total flight time was 71ns, well within the 100ns range of the 50ps TDC. Placing a tight ADC cut on both S1 and S2 (100 channels wide, 20–50% of the data), we eliminate most of the noise in the TDC spectrum with a further correction for time in the spill. We end up with the TDC distribution shown in Fig. 2.

We have been able to make a precise time measurement because of the high light output of relativistic Au ions in scintillator. The ions lose ≈ 2.2 GeV in S1 and ≈ 7.7 GeV in S2. Assuming it takes ≈ 100 eV to produce a photon, this leads to 2.2×10^7 photons from S1. Known saturation of the scin-

Fig. 1. Experimental setup in the Beam 40 line at the Bevalac. Scintillator S1 is $10 \times 2 \times 1.8\text{mm}^3$ and S2 is $10 \times 2 \times 6\text{mm}^3$. At the "TOF START" position, both scintillators are placed in a vacuum box to get the relative time offset. This is the T0 position. Beam was focused just upstream of the S1 scintillator, with 30% of the full beam hitting S1.

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Fig. 2. Final TDC resolution after removing residual ADC and clock correlations is shown to be $\sigma = 58\text{ps}$.

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tillator reduces this light output significantly, but there are still hundreds of photons on the photocathode within 25ps.

Our measurements can be improved in at least two simple ways. To avoid difficulties with correction for the S1 scintillator, we are arranging to have a duplicate of this scintillator which can be plunged just upstream of the S1 position. Thus we can measure its effect directly. We also plan to replace the S1 and S2 scintillators with small diffusing surface Čerenkov light sources. This will reduce the total number of photons but all photons will arrive at the photocathode "simultaneously".

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Advances in Solid State Nuclear Track Detectors*

P.B. Price[†] and M.H. Salamon[†]

A new source of natural tracks in mica has been discovered: one due to recoiling atoms struck by alpha particles from radioactive impurities. These submicron tracks have a radiation-damage rate and thermal stability similar to that expected for a slowly moving monopole-nucleus bound state and are a valuable benchmark in an ongoing search for slow, supermassive magnetic monopoles. Plastic track detectors are being used to discover new modes of radioactive decay involving monoenergetic heavy ion emission. Bevalac studies show that plastic track detectors can be used to identify relativistic nuclei with Z/β from ~ 6 to ~ 120 with a charge resolution $\sigma_Z < 0.25e$. The charge resolution obtained is comparable to the irreducible limit set by fluctuations in energy loss and is consistent with that expected of a track-formation model based on the effects of both K-shell ionization and restricted energy loss. Ad-

vances in automation of scanning and measurements are opening up new physics applications requiring high statistics and resolution. Examples include searches for quark-nucleus complexes and anomalous mean free paths of projectile fragments produced in collisions at higher energies than are available at the Bevalac; analysis of thousands of tracks of ultraheavy cosmic ray nuclei to be collected on the NASA LDEF missions; and hybrid experiments such as the University of Chicago Spacelab II CRNE ultra high energy cosmic ray experiment and the EXAM heavy antinucleus experiment.

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* Abstract of opening lecture of 13th International Conference on Solid State Nuclear Track Detectors, Rome, Italy, September 23-27, 1985.

† Also at Space Sciences Laboratory

A Tracking Detector for Mid-Rapidity Particles at a Collider

L.S. Schroeder

A working group¹ convened at the 1985 BNL Detector Workshop² to consider a continuation of a detector concept developed at the 1984 Detector Workshop at LBL.³ At the LBL Workshop a preliminary design⁴ was developed for a detector to track hadrons produced near mid-rapidity at relatively low collider energies of a few GeV/nucleon in each beam. For the present Workshop we extended consideration to the much higher energies and correspondingly increased yields of charged particles available with RHIC.

The physics objectives for such a device include: 1) measurement of single-particle distributions to determine among other things the "nuclear temperature" for different particles; 2) strange particle fractions; 3) study of high p_T particles; 4) measuring the energy dependence of the abundance of protons in the central region to see if one can differentiate between the so-called "stopping" and "transparency" regimes; 5) Hanbury-Brown/Twiss like-particle interferometry to determine the space-time extent of the emitting source; and 6) fluctuations in dn/dy (albeit over a limited Δy range centered at mid-rapidity). The detector would track charged particles produced near mid-rapidity, i.e., $y_{cm} < 1$ (corresponding to $40^\circ \leq \theta \leq 140^\circ$), with a $\Delta\phi=45^\circ$ bite. The detector was designed for the case of maximum particle yield; namely, Au+Au central collisions at 100+100 GeV/nucleon. HIJET generated events indicate that about 4000 charged particles are expected over the full solid angle for such a case, with ~ 100 –200 particles/steradian being emitted at mid-rapidity with average momenta in the range of 400–500 MeV/c. Thus, the energy range to be covered by the detector is relatively low, allowing the use of well-known particle identification techniques.

The layout for the mid-rapidity tracker (MRT) is shown in Figs. 1(a) and 1(b). The interaction region (here assumed to be as large as 1 meter) is surrounded by a central detector for detecting both charged particle and sampling photon multiplicities. This multiplicity shroud contains two layers of pro-

Fig. 1. Schematic of the mid-rapidity tracker (MRT) consisting of: multiplicity shroud, planar TPC, magnet, drift chambers (DC) and time-of-flight wall (TOF). Fig. 1(a) plan view of MRT.

XBL 8510-4271

Fig. 1(b) elevation view of MRT. XBL 8510-4272

portional tubes with pad read-outs, separated by 0.5–1.0 radiation lengths of Pb. Thus, the inner layer will have a summed signal $\sim \sum n_{chg}$, while the outer layer will have a signal $\sim \sum n_{chg} + x \sum n_\gamma$, where x =fraction of photons converting in the Pb. Charged particles produced near mid-rapidity will be tracked by a system consisting of: 1) a planar TPC (with good pattern recognition capabilities) located 0.5 meters from the center of the interaction region—here straight-line trajectories should be easy to sort out; this is followed by 2) a bending magnet ($\int B dl = 5 \text{ kG}\cdot\text{m}$, $\Delta p/p \sim 0.5\%$), and 3) sets of drift chambers (DC). The well-defined vertical location of the interaction point in RHIC is to be utilized in the track reconstruction. At the back of the tracking system, 3 meters from the center of the interaction region, is a time-of-flight wall (TOF) made of plastic

scintillators. Good particle separation ($\pi/K/p$) can be made up to momenta of 1.0–1.2 GeV/c using TOF information only. No attempt was made to place end-cap detectors on the central multiplicity shroud to cover the more forward angles. However, we simply note that a detector like the MRT could be used in conjunction with other detectors which study production of particles at relatively large rapidities (i.e., forward angles).

Two levels of triggers were considered: 1) minimum bias, and 2) events with extreme conditions. A minimum bias trigger can be obtained by placing scintillators as close to the beam pipes as possible (perhaps with a "Roman-pot" arrangement inside the beam pipe) several meters downstream on both sides of the interaction region. Their precise location along the beam is chosen to guarantee that they will intercept particles from beam fragmentation events (peripheral processes). At the same time, the large numbers of particles emitted in central collisions will also ensure that some of them will be detected by these counters. The time difference determined from the fast signals of these counters can also be used to determine that an interaction came from the prescribed crossing region and was not the result of a single beam interaction (false halo trigger) upstream of the region. There also exists the possibility of using a threshold level on the output of these counters as a multiplicity control. The group felt strongly that a large sample of minimum-bias events should be analyzed at an early stage of the nucleus-nucleus program.

Clearly the primary interest is in central collisions which provide the largest overlap of nuclear matter, leading to the possible formation of the quark-gluon plasma. A high multiplicity trigger developed from the multiplicity shroud of the MRT will provide a way of triggering on central events. At the same time triggers which are associated with extreme conditions would be developed. These include fluctuations in η ($dn/d\eta$) or ϕ , high p_T observed in the tracking system and electromagnetic versus hadronic components in the multiplicity shroud. Fig. 2 shows the hit pattern of charged particles at the far edge of the magnet aperture resulting from a HIJET

generated central event for Au + Au collisions at 100 GeV/nucleon in each beam. Fifty-one charged particles are distributed over the exit aperture of the magnet. The particles are well separated and at first glance one might conclude that the tracking system is underdesigned. However, since "real events" might contain fluctuations which are a factor of two or more in particle number, we do not feel that this is the case.

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Fig. 2. Hit pattern of charged particles at exit of magnet aperture. The 51 particles were obtained from a HIJET central collision event, $67.5^\circ \leq \theta \leq 112.5^\circ$ and $\phi = 0-45^\circ$ for this case. XBL 8510-4273

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Presented at the Conference on Quark Confinement and Liberation: Numerical Results and Theory, Lawrence Berkeley Laboratory, Berkeley, CA, May 22-24, 1985; and to be published in the Proceedings, F.R. Klinkhamer and M.B Halpern, eds., World Scientific (1985).

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Target Fragmentation in Intermediate Energy Heavy Ion Collisions

Invited paper presented at the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden,
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LÖHNER, H. See GUSTAFSSON, H.-A. LBL-18949

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First Operation of the LBL ECR Ion Source with the 88-Inch Cyclotron

Invited talk presented at the 1985 Particle Accelerator Conference on Accelerator Engineering and Technology,
Vancouver, B.C., Canada, May 13-16, 1985

LYNEIS, C.M. LBL-18501

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Invited talk presented at the Eighth Conference on the Application of Accelerators in Research and Industry,
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MACCHIAVELLI, A.O. See STEPHENS, F.S. LBL-19113

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MEYERHOF, W.E., R. Anholt, J. Eichler, H. Gould, Ch. Munger, J. Alonso, P. Thieberger, H.E. Wegner LBL-20018

Atomic Collisions with Relativistic Heavy Ions III: Electron Capture

Phys. Rev. A

MIGNEREY, A.C. See CHARITY, R.J. LBL-20383

MILLER, J. See KREBS, G.F. LBL-18267

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Trends in The Study of Light Proton Rich Nuclei

Presented at the ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, IL, September 8-13, 1985

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Actinide Production in Reactions of Heavy Ions with ^{238}Cm

Phys. Rev. C

MORAVCSIK M.J. See CONZETT, H.E. LBL-18881

MORETTO, L.G. LBL-19806

Compound Nucleus Studies with Reverse Kinematics

Invited talk presented at the Conference on Nuclear Structure with Heavy Ions, Legnaro, (Padova), Italy, May
27-31, 1985.

MORETTO, L.G. See MORRISSEY, D.J. LBL-18688

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Masses and of the Businaro-Gallone Point

Invited talk presented at the International Conference on Nuclear Physics, Bombay, India, December 27-31,
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MORETTO, L.G., M.A. McMahan, L.G. Sobotka, G.J. Wozniak LBL-19030

Compound Nucleus Emission of Complex Fragments at Low and Intermediate Energies

Invited talk presented at the XIII International Workshop on Gross Properties of Nuclei and Nuclear Excita-
tions, Hirschegg, Austria, January 14-19, 1985.

MORIKAWA, Y., A. Iwazaki LBL-20175

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NITSCHKE, J.M. LBL-20196

Secondary Beams and the Synthesis of Exotic Nuclei

Invited talk presented at the workshop on Intermediate Energy Heavy Ion Physics, Oak Ridge, TN, September 23-25, 1985

NITSCHKE, J.M. See WILMARTH, P.A. LBL-19000

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Presented at the International Conference on Nuclear Data for Basic and Applied Science, Santa Fe, NM, May 13-17, 1985

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OLSON, D.L. LBL-18712

Looking for Anomalons with a Segmented Čerenkov Detector

Presented at the 7th High Energy Heavy Ion Study, Darmstadt, W. Germany, November 7-12, 1984

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An Analysis of Angular Momentum Projected Hartree-Fock-Bogoliubov Wave Functions in Terms of Interacting Bosons

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Experiments with Light Ions at the CERN Super Proton Synchrotron

Invited talk presented at the 7th High Energy Heavy Ion Study, GSI Darmstadt, W. Germany, October 8-12,
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PUGH, H.G. See HARRIS, J.W. LBL-19114

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Submitted to Nucl. Phys. A

RANDRUP, J. LBL-20914

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Invited paper for the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden, 10-14
June 1985

RANDRUP, J. LBL-20916

Transfer-Induced Transport in Slightly Damped Nuclear Reactions

Nucl. Phys. A

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RASMUSSEN, J.O., M.W. Guidry, L.F. Canto LBL-19125

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Presented at the Symposium on Semiclassical Descriptions of Atomic and Nuclear Collisions, Copenhagen,
Denmark, March 25-28, 1985

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RING, P., W. Pannert LBL-18846

Microscopic Analysis of Angular Momentum Projected HFB-States in Terms of Interacting Bosons

Presented at the International Symposium on Nuclear Shell Models, Philadelphia, PA October 31 - November 2, 1984

RIOUX, C. See CONZETT, H.E. LBL-19795

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RITTER, H.G., K.G.R. Doss, H.-A. Gustafsson, H.H. Gutbrod, K.H. Kampert, B. Kolb, H. Löhner, B. Ludewigt, A.M. Poskanzer, A. Warwick, H. Wieman LBL-20086

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Invited talk presented at the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden,
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ROBLEDO, L.M., J.L. Egido, P. Ring LBL-19520

A Microscopic Description of Boson- and Fermion- Alignment in Octupole Bands of Actinide Nuclei

Nucl. Phys. A **449**, 201 (1986).

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Phys. Lett. **156B**, 27 (1985).

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SCHALL, D. See HARRIS, J.W. LBL-19114

SCHÄDEL, M. See ARMBRUSTER, P. LBL-18581

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SCHMIDT, H.R., M. Bantel, Y. Chan, S.B. Gazes, S. Wald, R.G. Stokstad LBL-19910

A Segmented Position-Sensitive Plastic Phoswich Detector

Nucl. Inst. and Methods A **242**, 111 (1985).

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Strong Interactions at all Densities in a Chiral Soliton Model Coupled to Quarks

Phys. Lett. **152B**, 231 (1985).

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High Spin Properties of Some Nuclei Around $A=160$

Proceedings of the Niels Bohr Centennial Conference on Nuclear Structure 1985, Copenhagen, Denmark, May 20-25, 1985; Nuclear Structure 1985. R. Broglia, G.B. Hagemann & B. Herskind (editors), Elsevier Science Publishers B.V., pp. 363-378 (1985).

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Physics Today

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Invited talk presented at the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden, June 10-14, 1985; Nucl. Phys. A

STEPHENS, F.S. See DELEPLANQUE, M.A. LBL-18118

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STEPHENS, F.S., M.A. Deleplanque, R.M. Diamond, A.O. Macchiavelli, J.E. Draper LBL-19113

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Phys. Rev. Lett. **54**, 2584 (1985).

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The Dependence of Heavy-Ion Induced Adhesion on Energy Loss and Time

Journal of Material Research

STRÖBELE, H. See HARRIS, J.W. LBL-19114

SUGIMOTO, K. LBL-18791

Use of Exotic Nuclear Beams for Nuclear Structure Studies

Invited talk presented at the 7th High Energy Heavy Ion Study, Darmstadt, W. Germany, October 8-12, 1984

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A Mnemonic for Feigenbaum's Universal Number δ

ŚWIATECKI, W.J. LBL-19222

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ŚWIATECKI, W.J. See TREINER, J. LBL-18477

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ŚWIATECKI, W.J. See BŁOCKI, J. LBL-20126

ŚWIATECKI, W.J. See DORSO, C.O. LBL-20365

SYMONS, T.J.M. LBL-20136

Recent Progress in Applications of High Energy Ion Beams to Nuclear Structures and Atomic Physics

Invited talk presented at the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden,
June 10-14, 1985

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SYMONS, T.J.M. See GREINER, D.E. LBL-18486

SZCZEKOWSKI, M. See BELL, W. LBL-20971

SZWED, R. See BELL, W. LBL-20970

SZWED, R. See BELL, W. LBL-20971

TAKAHASHI, N. See TANIHATA, I. LBL-18821

TAKAHASHI, N. See TANIHATA, I. LBL-19904

TAKAHASHI, N. See TANIHATA, I. LBL-20244

TANIHATA, I. LBL-18777

Coplanarity of Two-Proton Emissions in 400 MeV/nucleon Ne + NaF, Pb Reactions

Invited paper presented at the 7th High Energy Heavy Ion Study, GSI, W. Germany, October 8-12, 1984

TANIHATA, I. LBL-20245

Measurement of Interaction Cross Sections and Nuclear Radii of Unstable p-Shell Nuclei

Presented at the Accelerated Radioactive Beams Workshop, TRIUMF, Vancouver, B.C., Canada, September 5-7, 1985

TANIHATA, I. LBL-18589

Nuclear Physics Using Unstable Nuclear Beams

Hyperfine Interactions **21**, 251 (1985).

TANIHATA, I., H. Hamagaki, O. Hashimoto, S. Nagamiya, Y. Shida, N. Yoshikawa, O. Yamakawa, K. Sugimoto, T. Kobayashi, D.E. Greiner, N. Takahashi, Y. Nojiri LBL-18821

Measurements of Interaction Cross Sections and Radii of He Isotopes

Phys. Lett. **160B**, 380 (1985).

Appendix I Publications

- TANIHATA, I., H. Hamagaki, O. Hashimoto, Y. Shida, N. Yoshikawa, K. Sugimoto, O. Yamakawa, T. Kobayashi, N. Takahashi LBL-19904
Measurements of Interaction Cross Sections and Nuclear Radii of Li Isotopes
Phys. Rev. Lett.
- TANIHATA, I., H. Hamagaki, O. Hashimoto, Y. Shida, N. Yoshikawa, K. Sugimoto, O. Yamakawa, T. Kobayashi, N. Takahashi LBL-20244
Measurements of Interaction Cross Sections and Nuclear Radii in Light p-shell region
Phys. Rev. Lett.
- THIEBERGER, P. See ANHOLT, R. LBL-20019
- THIEBERGER, P. See MEYERHOF, W.E. LBL-20018
- TINCKNELL, M.L. See HARRIS, J.W. LBL-19114
- TRAUTMANN, N. See ARMBRUSTER, P. LBL-18581
- TREINER, J. See DORSO, C.O. LBL-20365
- TREINER, J., W.D. Myers, W.J. Świątecki, M.S. Weiss LBL-18477
Bulk Compression Due to Surface Tension in Hartree-Fock, Thomas-Fermi and Droplet Model Calculations
Nucl. Phys.
- TREINER, J.R. See KOLEHMAINEN, K. LBL-18513
- TRENTALANGE, S. See BARASCH, E. LBL-17065 REV.
- TRENTALANGE, S. See ABACHI, S. LBL-19891
- TRÜOL, P. See CROWE, K.M. LBL-18861
- TSERRUYA, I. See BUDZANOWSKI, A. LBL-17937
- TSERRUYA, I. See STOKSTAD, R.G. LBL-20302
- TSERRUYA, I. See WALD, S. LBL-19403
- ULLALAND, O. See BELL, W. LBL-20970
- ULLALAND, O. See BELL, W. LBL-20971

Appendix I Publications

VAN BIBBER, K. See WALD, S. LBL-19403

VAN DER PLICHT, J. See KREBS, G.F. LBL-18267

VATER, P. See DERSCH, G. LBL-18726

VERMEULEN, D. See ARMBRUSTER, P. LBL-18581

VICENTE, J. See KREBS, G.F. LBL-18267

VON GUNTEN, H.R. See ARMBRUSTER, P. LBL-18581

WAKAI, M. See SANO, M. LBL-18740

WALD, S. See BUDZANOWSKI, A. LBL-17937

WALD, S. See SCHMIDT, H.R. LBL-19096

WALD, S. See SCHMIDT, H.R. LBL-19910

WALD, S., S.B. Gazes, C.R. Albiston, Y. Chan, B.G. Harvey, M.J. Murphy, I. Tserruya, R.G. Stokstad, P.J. Countryman, K. Van Bibber, H. Homeyer LBL-19403
Study of Transfer and Breakup Processes in Reactions of 11- and 17-MeV/nucleon $^{20}\text{Ne} + ^{197}\text{Au}$
Phys. Rev. C **32**, 894 (1985).

WARWICK, A. See GUSTAFSSON, H.-A. LBL-18949

WARWICK, A. See GUSTAFSSON, H.-A. LBL-18401

WARWICK, A. See WIEMAN, H. LBL-19057

WARWICK, A. See DOSS, K.G.R. LBL-18948

WARWICK, A. See RITTER, H.G. LBL-20086

WARWICK, A.I. See HECKMAN, H.H. LBL-19031

WEGNER, H.E. See ANHOLT, R. LBL-20019

WEGNER, H.E. See MEYERHOF, W.E. LBL-20018

WEISS, M.S. See TREINER, J. LBL-18477

WEISS, M.S. See DORSO, C.O. LBL-20365

WELCH, R.B. LBL-19010

Actinide Production from Xenon Bombardments of Curium-248

Ph.D. Thesis

WELCH, R.B. See ARMBRUSTER, P. LBL-18581

WELCH, R.B. See MOODY, K.J. LBL-20246

WIEMAN, H. See GUSTAFSSON, H.-A. LBL-18949

WIEMAN, H. See GUSTAFSSON, H.-A. LBL-18401

WIEMAN, H. See DOSS, K.G.R. LBL-18948

WIEMAN, H. See RITTER, H.G. LBL-20086

WIEMAN, H., K.G.R. Doss, H.-A. Gustafsson, H.H. Gutbrod, B. Kolb, H. Löhner, B. Ludewigt, A.M. Poskanzer, T. Renner, H.G. Ritter, A. Warwick LBL-19057

Two Particle Correlations from Relativistic Nuclear Collisions

Presented at the 7th High Energy Heavy Ion Study, GSI, Darmstadt, Germany, October 8-13, 1984.

WILDENTHAL, B.H. See ÄYSTÖ, J. LBL-19757

WILMARTH, P. See ARMBRUSTER, P. LBL-18581

WILMARTH, P.A., J.M. Nitschke, P.K. Lemmertz, R.B. Firestone LBL-19000

Beta-Delayed Proton Precursors with $59 < Z < 62$

Zeitschrift für Physik A

WIRTH, G. See ARMBRUSTER, P. LBL-18581

WOLF, K.L. See HARRIS, J.W. LBL-19114

WOZNAK, G.J. See MORETTO, L.G. LBL-18720

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YAMAKAWA, O. See TANIHATA, I. LBL-19904

YAMAKAWA, O. See TANIHATA, I. LBL-20244

YASHITA, S. See ARMBRUSTER, P. LBL-18581

YOO, E. See CROWE, K.M. LBL-18861

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YOO, E. See FRANKEL, K.A. LBL-16000

YOSHIKAWA, N. See TANIHATA, I. LBL-18821

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YOSHIKAWA, N. See TANIHATA, I. LBL-20244

ZAJC, W.A. See CROWE, K.M. LBL-18861

ZAJC, W.A. See FRANKEL, K.A. LBL-16000

ZHOU, Z.Y., E.C. Schloemer, M.D. Cable, M. Ahmed, J.E. Reiff, J. Cerny LBL-18853

Additional Beta-Delayed Protons from the $T_z = -3/2$ Nuclei ^{21}Mg , ^{25}Si , ^{29}S , and ^{41}Ti

Phys. Rev. C **31**, 1941 (1985).

Theses

Actinide Production from Xenon Bombardments of Curium-248*Robert B. Welch*

Production cross sections for many actinide nuclides formed in the reaction of ^{129}Xe and ^{132}Xe with ^{248}Cm at bombarding energies slightly above the Coulomb barrier were determined using radiochemical techniques to isolate these products. These results are compared with cross sections from a $^{136}\text{Xe}+^{248}\text{Cm}$ reaction at a similar energy. When compared to the reaction with ^{136}Xe , the maxima in the production cross section distributions from the more neutron deficient projectiles are shifted to smaller mass numbers, and the total cross section increases for the production of elements with atomic numbers greater than that of the target, and decreases for lighter elements. These results can be

explained by use of a potential energy surface (PES) which illustrates the effect of the available energy on the transfer of nucleons and describes the evolution of the di-nuclear complex, an essential feature of deep-inelastic reactions (DIR), during the interaction. The other principal reaction mechanism is the quasi-elastic transfer (QE). Analysis of data from a similar set of reactions, ^{129}Xe , ^{132}Xe , and ^{136}Xe with ^{197}Au , aids in explaining the features of the Xe+Cm product distributions, which are additionally affected by the depletion of actinide product yields due to deexcitation by fission. The PES is shown to be a useful tool to predict the general features of product distributions from heavy ion reactions.

Non-Collective High-Spin States in ^{148}Dy *Eugene Liviu Dines*

General physical concepts regarding nuclear high spin states are given. The high spin states in ^{148}Dy ($Z=66$, $N=82$) were produced via the reaction ^{112}Cd (Pb backed) ($^{40}\text{Ar}, 4n$) at $E_{\text{lab}}=175$, at the 88-Inch Cyclotron at Lawrence Berkeley Laboratory.

The data were collected with an array of 12 Compton-suppressed pure Ge detectors, and sorted in the $E_\gamma \times E_\gamma$, 2D-coincidence matrix format for prompt and delayed gates placed on the RF-Ge TAC (which can give the time distribution of a given coincident γ ray relative to formation of the compound nucleus). A Ge-Ge TAC was also recorded, thus giving one distributions of time intervals elapsed between detections of any given two coincident γ rays. The data were also sorted in the RF-Ge TAC $\times E_\gamma$, Ge-Ge TAC $\times E_\gamma$, (0° , 90°), (0° , 0°), and (90° , 90°) formats, where the last three gave information about the angular correlations. The format (0° , 90°), for example, refers to coincidences

between a given γ ray detected in the backward direction and another detected at 90° with respect to the beam axis, respectively.

Methods for placing gates on various transitions above and below the 480 nsec isomer at 10^+ (known from previous work), as well as for calculating transition intensities and their associated errors are given. Calculations were made of angular correlations for multiple γ ray cascades, assuming non-zero-width distributions in m -states for some given spin state, were done and compared to experimental values. Analysis of RF-Ge and Ge-Ge TAC spectra for transitions above the 480 nsec isomer implied lifetimes of $\lesssim 5$ nsec (except for the 327.2 keV transition). Using such analysis some 19 new γ ray transitions were discovered above the isomer, thereby extending the ^{148}Dy level scheme up to spin $I=31\hbar$. Assignments of spins and parities for the new levels are made based on information obtained from angu-

lar correlations and the lifetime limits. Previous work on the 11 transitions below the 480 nsec isomer is confirmed.

Below the isomer the even spin and parity levels (up to 10^+) have been interpreted as excited states of the $\pi h_{11/2}^2$ configuration (with the ^{146}Gd core unexcited), while the 3^- , 5^- , and 7^- states have been interpreted as: the $(\pi h_{11/2}^2)_0 \times 3^-$ (3^- refers to the core octupole), $(\pi h_{11/2} s_{1/2}) 5^-$ and $(\pi h_{11/2} d_{3/2}) 7^-$ configurations, respectively. Above the 480 nsec isomer, the 11^- , 12^- , and 13^- levels at $E^*=3980$, 4476,

and 4851 keV, respectively, have been discussed with relation to levels of the two-particle-core-octupole coupling $(\pi h_{11/2}^2)_{I'} \times 3^-$, where $I'=10$ for the 12^- and 13^- , and $I'=8$ and 10 for the 11^- . Theoretical values for energies of the 11^- (after interaction matrix diagonalization in the 2D basis made by $I'=8$ and 10) and the 13^- levels are obtained using second-order perturbation theory, and found to be in reasonable agreement with the experimental values. The rest of the experimental levels above the 480 nsec isomer are interpreted as deformed-independent-particle-model states.

Invited Papers

Presented at the 7th High Energy Heavy Ion Study, GSI, Darmstadt, W. Germany, October 8–12, 1984:

Phase Transitions in Nuclear Matter

N.K. Glendenning

Use of Exotic Nuclear Beams for Nuclear Structure Studies

K. Sugimoto

Coplanarity of Two-Proton Emissions in 400 MeV/nucleon Ne + NaF, Pb Reactions

I. Tanihata

Experiments with Light Ions at the CERN Super Proton Synchrotron

H.G. Pugh

Cluster Production and Entropy

H.-A. Gustafsson

Flow

H.G. Ritter

Two Particle Correlations from Relativistic Nuclear Collisions

H. Wieman

Light Particle Emission at Large Angles in 0.8 A GeV La + La Collisions

Y. Miake

Experiments Using Beams of Unstable Nuclear Isotopes - (Interaction Cross Sections and The Radii of He Isotopes)

I. Tanihata

Study of 1.7A GeV ^{56}Fe Projectile Fragment Mean Free Paths in CR-39 Track Detectors

M.L. Tincknell

Evidence Against “Anomalon” Production in High-Energy Heavy-Ion Collisions

M.L. Tincknell

Presented at the International Conference of Nuclear and Radiochemistry, Lindau, Germany, October 8–12, 1984:

Recent Results of Heavy Ion Reactions

D.C. Hoffman

Presented at the Conference on Instrumentation for Heavy Ion Nuclear Research, ORNL, Oak Ridge, TN, October 22–24, 1984:

High Spin States

R.M. Diamond

The GSI-LBL Plastic Ball/Wall Spectrometer

H.-A. Gustafsson

The Berkeley High-Resolution Ball

R.M. Diamond

Report on the 1984 LBL Workshop on Detectors for Relativistic Nuclear Collisions

L.S. Schroeder

The HISS Spectrometer

D.E. Greiner

Phoswitch Detectors and the Plastic Box

R.G. Stokstad

Presented at the Eighth Conference on the Application of Accelerators in Research and Industry, North Texas State University, Denton, TX, November 12–14, 1984:

Performance of the LBL ECR Ion Source

C.M. Lyneis

Presented at the 1984 International Chemical Congress of Pacific Basin Societies, Honolulu, Hawaii, December 19, 1984:

Heavy Ion Reactions on Curium Targets

D.C. Hoffman

Appendix II PhD Theses and Invited Papers

Presented at the International Conference on Nuclear Physics, Bombay, India, December 27–31, 1984:

Fission Along the Mass Asymmetry Coordinate: An Experimental Evaluation of the Conditional Saddle Masses and of the Businaro-Gallone Point

L. G. Moretto

Study of Transfer and Breakup Reactions with the Plastic Box

R.G. Stokstad

Presented at the XIII International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 14–19, 1985:

Fission along the Mass Asymmetry Coordinate. an experimental evaluation of the conditional saddle masses and of the Businaro-Gallone point

L.G. Moretto

Experimental Search for New Forms of Nuclear Matter

S. Nagamiya

Soliton Matter as a Model of Dense Nuclear Matter

N.K. Glendenning

Compound Nucleus Emission of Complex Fragments at Low and Intermediate Energies

L.G. Moretto

Shape Dependent Finite-Range Droplet Model

P. Möller

Presented at the High Energy Seminar, Physics Department, Indiana University, Bloomington, Indiana, February 12, 1985:

Antiprotons in the Cosmic Rays: Harbingers of the Exotic?

M.H. Salamon

Presented at the Physics Department Colloquium, University of Michigan, Ann Arbor, Michigan, March 11, 1985:

Exotic Modes of Radioactive Decay by Spontaneous Emission of Complex Nuclei

P.B. Price

Presented at the College of Charleston and ACS Meeting, March 20, 1985:

How Many Chemical Elements Are There?

D.C. Hoffman

Presented at the Argonne National Laboratory Physics Colloquium, March 22, 1985:

Compression and Expansion in Relativistic Nuclear Collisions

A.M. Poskanzer

Presented at the Niels Bohr Centennial Symposium on Semi-classical Descriptions of Atomic and Nuclear Collisions, Copenhagen, Denmark, March 25–28, 1985:

Friction in Nuclear Dynamics

W. J. Świątecki

Transfer Involving Deformed Nuclei

J.O. Rasmussen

Invited Lectures presented at the Summer Study on Nucleus-Nucleus Collisions from the Coulomb Barriers up to Quark-Gluon Plasma, Erice, Sicily, April 10–22, 1985:

Introduction to QCD Thermodynamics and The Quark-Gluon Plasma

M. Gyulassy

Presented at the American Physical Society Meeting, Washington, D.C., April 24–27, 1985:

Exotic Modes of Radioactive Decay by Spontaneous Emission of Complex Nuclei

P.B. Price

Presented at the American Chemical Society Meeting, Miami Beach, FL, April 28–May 3, 1985:

Bound and Unbound Cluster Yields in Relativistic Nuclear Collisions

H. Wieman

Collective Flow of Nuclear Matter

A.M. Poskanzer

Appendix II PhD Theses and Invited Papers

Probing Hot, Dense Nuclear Matter in Relativistic Nucleus-Nucleus Collisions for the Nuclear Equation of State

J. Harris

Presented at the 1985 Particle Accelerator Conference on Accelerator Engineering and Technology, Vancouver, B.C., Canada, May 13–16, 1985:

First Operation of the LBL ECR Ion Source with the 88-Inch Cyclotron

C.M. Lyneis and D.J. Clark

Presented at the Neils Bohr Centennial Symposium on Nuclear Structure, Copenhagen, Denmark, May 20–24, 1985:

High Spin Properties of Some Nuclei around $A=160$

F.S. Stephens

Presented at the Conference on Nuclear Structure with Heavy Ions, Legnaro (Padova), Italy, May 27–31, 1985:

Compound Nucleus Studies with Reverse Kinematics

L.G. Moretto

Presented at the Symposium on Electromagnetic Properties of High Spin States, A.F.I., Stockholm, Sweden, May 28–31, 1985:

HERA, The High Energy Resolution Array, and First Results

R.M. Diamond

Presented at the dedication of the Atlas accelerator at Argonne National Laboratory, June 3, 1985:

High Spin States in Nuclei

R.M. Diamond

Presented at the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden, June 10–14, 1985:

Flow of Nuclear Matter

H.G. Ritter

Appendix II PhD Theses and Invited Papers

Recent Progress in Applications of High Energy Ion Beams to Nuclear Structures and Atomic Physics
T.J.M. Symons

Summary Panel of the Conference
S. Nagamiya

Unresolved Gamma Rays from High Spin Studies
F.S. Stephens

Presented at the Gordon Conference on Nuclear Chemistry, New London, N.H., June 17–21, 1985:

High Spin States from the Berkeley Array
R.M. Diamond

Presented at the Isolde Seminar, EP Division, CERN, Geneva, Switzerland, June 27, 1985:

New Modes of Tunneling Radioactivity: Cluster Emission or Supersymmetric Fission?
P.B. Price

Presented at the Symposium of the Division of Nuclear Chemistry and Technology, ACS, Chicago, IL, August 26–30, 1985:

HERA, The Berkeley Array, and Early Results
R.M. Diamond

Presented at the International Symposium on Heavy Ion Physics, Mt. Fuji, Japan, August 27–31, 1984:

The Businaro-Gallone Transition, as observed in Complete Charge Distributions from Compound Nucleus Decay
L. G. Moretto

Presented at the Europhysics Study Conference on Synthesis and Structure of Exotic Nuclei and Atoms, Varna, Bulgaria, September 16-21, 1985:

Exotic Decay Modes Involving Monoenergetic Heavy Ion Emission
P.B. Price

Appendix II PhD Theses and Invited Papers

Presented at the Workshop on Intermediate Energy Heavy Ion Physics, Oak Ridge, TN, September 23–25, 1985:

Compression and Expansion

H.G. Ritter

Presented at the 13th International Conference on Solid State Nuclear Track Detectors, Rome, Italy, September 23–27, 1985:

Nuclear Tracks in Solids: Advances in Techniques and Applications

P.B. Price

Presented at the Radioactive Beam Workshop at TRIUMF, Vancouver, Canada, September 1985:

Experiments Using High-Energy Radioactive Beam

I. Tanihata

Appendix III Seminars

Monday Seminars

October 1, 1984	Prof. P. C. Sood Banaras Hindu Univ., India	Energy Levels of Odd-Odd Nuclei
October 15, 1984	Prof. Richard Muller UCB/LBL	Current Status of the Periodic Extinction Problem
October 22, 1984	Dr. Tom Humanic LBL	Pion Interferometry Measurements for the System 1.7 A GeV $^{56}\text{Fe} + ^{56}\text{Fe}$
October 29, 1984	Dr. Jay Marx LBL	Introduction to the SSC
October 30, 1984 Tuesday	Prof. O. Miyamura Osaka Univ.	New Results from JC-3 Studies of Nuclear Collisions Between 20 and 60 A GeV
November 5, 1984	GRADUATE STUDENTS	
November 12, 1984	Dr. George Smoot LBL - SSL	Spectrum of the Cosmic Background Radiation
November 19, 1984	Dr. Douglas Olson LBL	Reaction Cross Sections From a Segmented Čerenkov Detector
November 26, 1984	Prof. Isao Tanihata INS - LBL	Experiments Using Beams of Unstable Nuclear Isotopes (The Interaction Cross Sections and the Nuclear Radii of He Isotopes)
December 10, 1984	Dr. Arch Thiessen LANL	LAMPF II Including a Discussion of Recent Data on $[\pi, K]$ Obtained at Brookhaven
December 14, 1984 Wednesday	Prof. Steven Koonin California Institute of Technology	Subsaturation Phases of Nuclear Matter
December 17, 1984	Dr. Erwin Friedlander LBL	Interaction Properties of Projectile Fragments from the Bombardment of By Activation Methods

Appendix III Seminars

January 7, 1985	Prof. V. Devanathan Univ. of Madras, India	Quarks in Nuclei
January 14, 1985	Prof. David Boal Simon Frasier Univ.	Nuclear Phase Transitions
January 21, 1985	HOLIDAY	
January 24, 1985 Thursday	Dr. Scott Pratt Univ. of Minnesota	Pion Interferometry
January 28, 1985	GRADUATE STUDENTS	
February 4, 1985	Dr. Keith Griffioen Stanford Univ.	Giant Resonances in ^{238}U Studied by Coincident Electrofission (e, e'f)
February 6, 1985 Wednesday	Dr. L. Remsberg Brookhaven National Lab.	Stopping Power Measurements with 17 GeV/c protons
February 11, 1985	GRADUATE STUDENTS	
February 18, 1985	HOLIDAY	
February 25, 1985	Dr. Bernard Harvey LBL	Microscopic Calculation of Fragment Formation in Nucleus-Nucleus Collisions, 20 MeV/nucleon to 2 GeV/nucleon
March 4, 1985	GRADUATE STUDENTS	
March 11, 1985	Prof. Geoffery Chew UCB/LBL	Proposed Solution of the Lepton Puzzle
March 14, 1985 Thursday	Prof. Alfred Goldhaber SUNY	Nucleons as Knots (Skrymions as Nucleons)
March 18, 1985	Prof. Hermann Wollnik	On-line Separators for Studies
March 20, 1985 Wednesday	Prof. Hans Bethe Cornell Univ.	Supernova Theory
March 21, 1985 Thursday	Dr. Terry Goldman LASL	Quarklei: An Approach to Nuclei from QCD

Appendix III Seminars

March 26, 1985 Tuesday	Dr. Christopher Waltham TRIUMF Univ. of British Columbia	Rare Pion Decays at TRIUMF
April 1, 1985	GRADUATE STUDENTS	
April 15, 1985	Prof. J. L. Egidio LBL	Microscopic Description of the Compound Nuclei
April 22, 1985	No seminar due to Washington APS meeting	
April 29, 1985	Dr. Michael Hotchkis Univ. of Canberra/LBL	Studies of Light Neutron-rich Nuclei
May 6, 1985	GRADUATE STUDENTS	
May 20, 1985	Prof. Yeong Kim Purdue Univ.	Energy-Dependent Interaction Cross Sections and "Anomalons"
May 27, 1985	HOLIDAY	
June 3, 1985	Prof. Klaus Fabricius Univ. of Wuppertal	Simulation of Large N Models
June 24, 1985	Prof. Hugh Evans Queen's Univ., Kingston, Ontario and Caltech	Parity Violation in ^{18}F
July 25, 1985 Thursday	Prof. Rolf Siemssen KVI-Groningen	Heavy Ion Reaction Mechanisms At Intermediate Energies
August 8, 1985 Thursday	Dr. T. Staner Bartol Research Foundation	Cascade Calculations for pA Collisions at 20 - 1000 GeV
August 9, 1985 Friday	Prof. Yasuhiro Kitazoe Kochi University, Japan	A Cascade Model
August 12, 1985	Prof. Walter Greiner Univ. of Frankfurt	Positrons from Supercritical Fields
August 14, 1985 Wednesday	Prof. Walter Greiner Univ. of Frankfurt	Giant Nuclear Systems and/or New Particles in Connection with Positron Spectra
September 2, 1985	HOLIDAY	

Appendix III Seminars

September 16, 1985	Prof. Francois Lefebvres Univ. of Caan / LBL	Some Results of 35 MeV/nucleon Kr + Ar
September 23, 1985	Dr. Frans Klinkhamer LBL	On Nonperturbative Structure in Nuclear Field Theory
September 30, 1985	Divisional discussion Dr. J.M. Nitschke, Intro.	NSD Accelerator Initiative: Machine Characteristics

Appendix III Seminars

Bevalac Research Meetings

October 25, 1983	J. Rafelski University of Capetown	Clustered Quark Matter
October 30, 1984	Michel Lengevin IPN Orsay	New Neutron-Rich Light Isotopes Produced by Projectile Fragmentation at GANIL
November 13, 1984	Hans-Jurgen Besch CERN	Status Report on the RICH-Counters Used in the DELPHI Experiments at LEP
November 20, 1984	Walter Geist LBL	Recent Results from Light Ion Collisions in the ISR
November 29, 1984	Miklos Gyulassy LBL	Nuclear Stopping Power
December 11, 1984	Robert Brockmann GSI/LBL	Pion and Proton "Temperatures" in Relativistic Heavy Ion Reactions
December 18, 1984	Tom Humanic LBL	Pion Interferometry Studies of Relativistic Heavy-Ion Collisions Using the Intranuclear Cascade
January 24, 1985	René Brun CEA/N	Presentation of the Simulation Program GEANT3 for Detector and Experiment Design
January 29, 1985	Harvey Gould LBL-MMRD	Atomic Physics at a Relativistic Nuclear Collider
February 6, 1985	L. Remsberg Brookhaven National Laboratory	Stopping Power Measurements with 17 GeV/c Protons
February 12, 1985	Laszlo Csernai Univ. of Minnesota	Possible Solution to the Entropy Puzzle
February 19, 1985	James Symons LBL	New Detectors for HISS
February 26, 1985	Bo Andersson Lund	Part I--Hadronization of a Color Force Field According to the Lund Model

Appendix III Seminars

February 28, 1985	Bo Andersson Lund	Part II--Low $P_{\perp}$ -Interactions and Color Force Fields in Hadron-Hadron and Hadron-Nucleus Collisions in the Lund Model
March 7, 1985	Ed Remler William and Mary College	The So-Called Entropy Puzzle
March 14, 1985	Bo Andersson Lund	Color Force Fields and the Lund Model
March 26, 1985	Walt Benenson MSU	Heavy Ion Collisions
April 11, 1985	G. Odyniec LBL	Transverse Momentum Analysis of Collective Motion in Relativistic Nuclear Collisions
May 21, 1985	Stan Majewski Fermi Lab	Some New Ideas in High Energy Physics Detectors
May 28, 1985	D. Keane U.C. Riverside	Measurement of Collective Flow
June 4, 1985	Chuck McParland LBL	New Data Acquisition Projects at the Bevalac
June 11, 1985	Steve Trentalange U.C.L.A.	Single Lepton Production in Heavy Ion Collisions
June 18, 1985	Gene Barasch and Shawn Carlson U.C. Davis and LBL	Kaon Production in Relativistic Heavy Ion Collisions at the Bevalac
July 16, 1985	Ryoichi Wada GSI	Recent Results from the CERN SC
August 20, 1985	Joseph Cugnon University of Liège	Properties and Causes of Collective Flow
August 27, 1985	Charles Gruhn LBL	NA36 TPC Project
September 10, 1985	P. Ammiraju Brazil	Centauros and Other Exotic Events in Cosmic Rays

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